

EVALUATING THE POTENTIAL OF WELL PROFILING TECHNOLOGY TO LIMIT IRRIGATION WATER SALINITY IN CALIFORNIA VINEYARDS

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ABSTRACT. Grape growers in some regions of California are confronting problems with soil salinity. Improving irrigation water quality at the source well offers a potential solution to mitigate soil salinity issues in vineyards. Here, we utilized tracer-pulse technology and chemical analysis to assess flow and constituent contributions at various points throughout the depth profiles of three wells with known salinity problems. At the surface, all three wells had several chemical constituents measuring at concentrations higher than the recommended threshold for grapevines. Theoretical well manipulation effects were calculated to evaluate whether blocking inflow at each layer of each well's depth profile would improve overall water quality at the surface. The profiling technology effectively measured variation in flow and chemical contributions along each profile. As no strong chemical hotspots were detected and the distributions were relatively uniform/symmetric across each of the depth profiles, the theoretical well manipulation offered little improvement in overall well water quality without detrimental effects on volume pumping capacity. For example, in one well a manipulation inserted at 73- to 113-m below ground surface would reduce the overall concentration of several constituents of concern, but would be accompanied by a 41% reduction in well flow. While a well manipulation would have minimal effect for the three wells assessed in this study, this method could be an effective means of improving irrigation water quality for wells with stronger asymmetrical patterns of constituent contributions.

Keywords. Well monitoring, Water quality, Tracer-pulse, Grapevines.

In dry growing regions, soil salinization is a serious problem confronting sustainable production of irrigated crops. The United Nations Food and Agriculture Organization has estimated that each year 0.25 to 0.5 million ha of irrigated arable land are seriously damaged and lost from crop production due to salt accumulation in soils (FAO, 2002). Saline irrigation water, low rainfall, shifting water tables, and high evapotranspiration rates can all contribute to concentrating salts in crop root zones (Tregeagle et al., 2006). In some regions, soil salinization is likely to worsen under the increasing drought frequency predicted by climate change scenarios.

Soil salinity is an emerging problem for some major grape growing regions of California (Battany, 2007; 2008). Poor irrigation water quality, limited winter rainfall, and drip/deficit irrigation strategies, which are commonly used

to improve vineyard water use efficiency and fruit quality, are contributing to this problem in vineyards (Battany, 2007; 2008). When exposed to salinity, grapevines exhibit reduced photosynthesis and shoot elongation, sodium (Na) and chloride (Cl) toxicity in leaves, and sodium-potassium (K) imbalance (Walker et al., 1981; Garcia and Charbaji, 1993; Fisarakis et al., 2001; Shani and Ben-Gal, 2005). Since *Vitis vinifera* grapevines have been classified as moderately sensitive to salinity (Maas, 1990) and have only a modest capacity to exclude Cl ions, improving irrigation water quality prior to application could serve as an alternative strategy to avoid soil salinity issues in vineyards.

Discrete layers of a vertical well profile can often contribute disproportionately to chemical constituent concentrations of the bulk water extracted at the surface. Asymmetrical patterns of water quality can form as a consequence of vadose zone thickness, seasonal recharge, well depth, aquifer contamination, land use, and geology (e.g. chemical composition of parent rock) (Nightingale and Bianchi, 1980; Spalding and Exner, 1980; Beke et al., 1993; Hudak, 2001). Advanced well sampling techniques can identify vertical and asymmetrical patterns within wells, and a manipulation (e.g. a hydraulic manipulator or well patch) can then be used to minimize water extraction from problematic layers (Heller, 2008). Insertion of an inflatable packer over the screen section producing the asymmetry is a remediation technique which is commonly used for well zone isolation (Swanson, 1986). Eccles et al. (1976) were able to effectively reduce the dissolved nitrate

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concentration in a municipal drinking well from 20 to 4 mg L⁻¹ by installing an inflatable packer over the section of the well screen supplying the greatest nitrate concentration; this manipulation reduced total well flow by only a 25% (Eccles et al., 1977). Similarly, a temporary packer was installed into production wells contaminated with trichloroethylene (TCE) and perchloroethylene (PCE) (Coufal et al., 1984). Upon insertion of the packer, TCE and PCE concentrations dropped from 100 and 4 ppb to 7 and 0.5 ppb, respectively. Upon removal of the packer both TCE and PCE concentrations returned to their previously high levels, illustrating the packer's effectiveness (Coufal et al., 1984). These cases illustrate how profiling and well manipulation can improve overall water quality with a minimal loss in flow capacity, and offer growers a potentially cost-effective alternative to drilling replacement wells.

The tracer-pulse method is one advanced well sampling technique that can effectively measure well water velocity and contaminant variations with better resolution than conventional well sample collection methods and with less overall disruption to the well's operation. The tracer-pulse method calculates water velocity and variations with a dye point tool centered in the well at incremental depths throughout the well, providing a better cross-sectional interpretation of the areal and vertical variations in water quality than a conventional spinning tool and velocity log (Izbicki et al., 1999). As the tracer-pulse method does not require wellhead removal for effective measurements, the method can locate plumbing features inside the well column including the pump location, pump column holes, and well screen casing leaks.

Here, we assessed the utility of flow and chemical profiling with the objective of determining whether these techniques could be used to improve irrigation water quality in vineyards with known salinity problems. We paired flow and chemistry measurements with theoretical well manipulations along depth profiles of each well to determine whether vertical asymmetry exists in these wells and whether this strategy could be used to improve irrigation water quality.

MATERIALS AND METHODS

Three irrigation wells located in the Central Coast growing region of Paso Robles, California, were selected based upon pre-existing water quality problems. Vertical well sampling was performed by BESST Inc. Global Subsurface Technologies (San Rafael, Calif.) using the tracer-pulse method described by Izbicki et al. (1999). Each well was assessed using a chain access survey prior to sampling to identify how the tracer-pulse nozzle and tubing could best enter into each well with the pump in place as to not disturb flow. A flow meter attached to the well discharge line was used to analyze the average pumping rate during a 10- to 15-h irrigation cycle. Water was discharged from the well until the wellbore's water level maintained a constant water level during pumping. The

tracer-pulse nozzle and high pressure hose were then inserted into the well through the access identified by the chain access survey.

The tracer-pulse nozzle was filled with a fluid containing rhodamine red FWT (Fluorescent Water Tracing) 50 (Bright Dyes, Orlando, Fla.), an easily measured NSF (National Sanitation Foundation) 60-approved tracer, which was electro-pneumatically released by the tracer-pulse nozzle at various well depths based upon the different perceived flow rates throughout the well (fig. 1). The travel time of the tracer between well depths was measured at the surface by a fluorometer. Data were used to create a flow velocity profile from a series of injections between different tracer release depths.

Wells 1, 2, and 3 were sampled on 26, 19, and 20 August 2009, respectively. Water quality samples were collected from the well at intervals co-located with injection points using a miniaturized water pump/bailer. Samples were taken as point locations within larger intervals throughout the active screened depths of the well and composite samples were collected directly from the spigots (C_5) as a measure of overall water quality (fig. 1). Two sample replicates were taken for each depth and for each composite at the spigot. Samples were collected, preserved, stored, and analyzed in accordance with approved sampling containers, preservation techniques, and holding times (EPA, 2009). Following collection, samples were immediately shipped on ice to the University of California, Davis Analytical Laboratory (Davis, Calif.) for analysis. Water samples were analyzed for the following parameters: pH, electrical conductivity (EC), sodium adsorption ratio (SAR), Ca, Mg, Na, Cl, B, HCO₃, and CO₃. The Ca:Mg ratio was calculated from ionic Ca and Mg data. Very little variability was observed between replicates ($R^2 = 0.9977$), and an average of the two samples were used for theoretical calculations. Constituent thresholds for grapevine production were considered with respect to a maximum threshold (i.e. toxicity assessment) under the assumption that insufficient macro- or micro-nutrient supplies in irrigation water could be mitigated through supplemental fertigation.

Due to an obstruction by the pump bowls, data was not directly measured from the bottom portion of well 1 (see diagram, fig. 1). Flow for the bottom portion of the well was estimated based upon data from the upper portion of the well, spigot discharge, and comparison with wells of similar construction. Chemistry data from the bottom portion of the well was calculated based upon the flow estimates for the portion below the intake, chemistry data from above the intake, and chemistry data at the discharge. Consequently, the uncertainty for the bottom portion of the well was higher than that for the rest of the well, and it was not possible to calculate EC for the bottom of the well. In addition, as a result of very low flow rates, the contributions of depth intervals 137-149m below the ground surface (bgs) and 149- to 162-m bgs to well flow were negligible, and subsequently, these depths had no effect on any constituent's overall concentration.

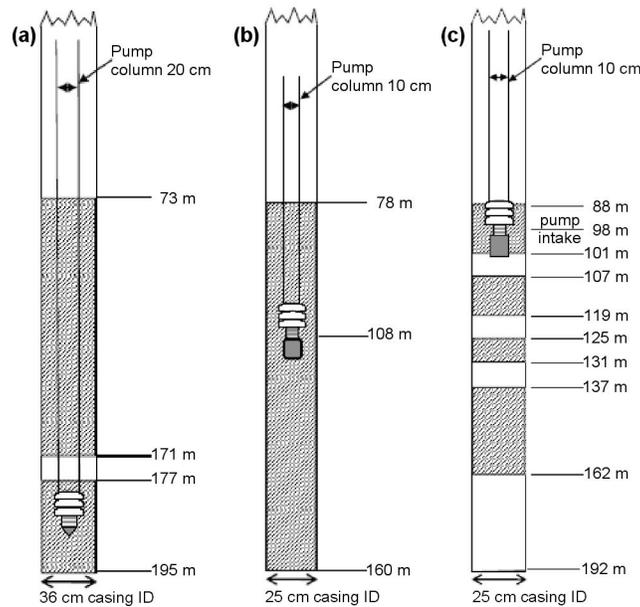


Figure 1. Depth profiles for three wells sampled in Paso Robles, Calif., using tracer-pulse well sampling technology. Wells 1 (a), 2 (b), and 3 (c) were sampled for a range of water constituents in August 2009. On the sampling date, the pumping water level for Wells 1, 2, and 3 was 94-, 101-, and 86-m bgs, respectively. Shaded areas denote screened areas where water enters the well. Intake pump and location is denoted by grey cylinder in middle of well casing.

Laboratory results were analyzed using the following mass balance equation to determine the concentration of each constituent entering the well between two depths to yield the incremental contribution of a constituent at a particular depth bgs (Izbicki et al., 1999):

$$C_a = (C_{z1}Q_{z1} - C_{z0}Q_{z0})/q_{z1-z0} \quad (1)$$

where C_a is the concentration in the water entering the well between depths z_0 and z_1 where z_1 is closer to the pump intake, C_z is the measured concentration of a constituent at depth z , Q_z is the volume of water passing depth z in the well per unit time, and q_{z1-z0} is the flow entering the well between points z_0 and z_1 .

Upon completion of the well assessment, well profile data was used to identify asymmetrical patterns of salinity recharge and to determine how a well manipulation would affect flow, chemical constituent concentrations, and overall salinity. Theoretical well manipulations at each depth interval were performed by eliminating the total flow contribution of each depth interval and calculating the total percent contributions of the remaining depth intervals. These calculations were performed assuming that the total flow contribution of the remaining depths and the incremental constituent contribution would not change, an assumption made based on observations of well characteristics during sampling. Theoretical constituent concentrations were then calculated by sequentially eliminating Q_z for each blocked depth interval and recalculating Q_z and q_z for all remaining intervals. The individual constituent concentrations at the remaining depths were then summed, such that the calculated theoretical concentration, C_T , equaled the sum of the concentration of each constituent at each depth multiplied by q_z , or:

$$C_T = \sum C_{Cz}q_z \quad (2)$$

where C_{Cz} is each constituent's incremental contribution at depth z . C_T values were calculated with each well depth interval individually eliminated and also for every well without any depth intervals eliminated for comparison with real water data to ensure accurate real-world comparison. C_T results from eliminated depths of each well were compared against calculated C_T values without a manipulation; depth-eliminated C_T results were compared against full-well C_T results instead of actual, spigot-collected data in order to compare water quality data that had been calculated through the same method (i.e., apples to apples). The depths to receive a potential manipulation were selected by summing the total percent reduction in C_T values for all constituents. The depth interval for each well with the greatest total percent reduction was selected as the one for which a manipulation would most greatly benefit total water quality.

RESULTS AND DISCUSSION

C_S results confirmed that all three wells exhibited poor water quality, as some of the chemical constituents exceeded recommended thresholds for grapevine production (table 1). pH, HCO_3 , and SAR were above recommended grapevine thresholds in all three wells, while Na and B were high in well 1 and Na was approaching the threshold in well 2. High pH and HCO_3 can lead to decreased N, P, Mg, Fe, Mn, B, Cu, and Zn bioavailability (Mengel et al., 1984), which will ultimately impact plant growth, yield, and berry and juice quality. SAR, a relative measure of sodium, calcium, and magnesium, and an indicator of salt hazard, was over three times the

Table 1. Each well's spigot-collected (C_s) and calculated (C_T) water quality results and recommended water quality thresholds for grapevine production.

	pH	EC ^[a]	SAR	Soluble Ca ^[b]	Soluble Mg ^[b]	Ca:Mg	Soluble Na ^[b]	Cl ^[b]	Soluble B ^[b]	HCO ₃ ^[b]	CO ₃ ^[b]	Flow ^[c]
Well 1 C_s	8.38	0.73	6.05	0.66	0.97	0.68	5.47	0.89	0.088	4.08	0.45	2646
(C_T)	(8.48)	(0.67)	(6.03)	(0.66)	(0.96)	(0.69)	(5.42)	(0.89)	(0.087)	(3.97)	(0.68)	
Well 2 C_s	8.08	1.05	2.95	2.42	2.78	0.87	4.74	2.48	0.056	3.2	0.38	756
(C_T)	(8.51)	(0.83)	(3.49)	(1.58)	(2.12)	(0.75)	(4.38)	(0.64)	(0.052)	(3.23)	(0.87)	
Well 3 C_s	8.30	0.70	2.46	1.77	1.97	0.90	3.07	1.75	0.034	3.10	0.52	945
(C_T)	(8.33)	(0.70)	(2.29)	(1.74)	(1.91)	(0.91)	(3.07)	(1.79)	(0.031)	(3.07)	(0.46)	
Threshold ^[d]	7.00 ^[e]	1.70 ^[f]	2.00 ^[f]	[e, g]	[e, g]	1.00 ^[h]	5.00 ^[i]	4.00 ^[i]	0.069 ^[i]	1.50 ^[i]	1.50 ^[i]	

[a] dS m⁻¹.

[b] meq L⁻¹.

[c] L min⁻¹.

[d] Grapevine threshold values shown as the ideal maximum threshold for each constituent.

[e] Keller (2007).

[f] Lantzke et al. (2007).

[g] It is recommended to look at the Ca:Mg ratio to gauge the appropriate threshold of Ca and Mg.

[h] Lambert et al. (2008).

[i] Ayers and Wescot (1994).

recommended threshold in well 1. Increased water infiltration problems may occur as a result of high SAR/low EC concentrations (Suarez et al., 2006). Based on the EC and SAR C_S values, well 1 demonstrated a moderate risk of salinity-related infiltration problems, whereas both wells 2 and 3 were of low risk of encountering infiltration problems (Hopkins et al., 2007). Boron levels even lower than those measured from well 1 have been detrimentally associated with reduced grapevine canopy development in another study (Yermiyahu et al., 2007).

C_S and C_T values were found to be very similar for all three wells ($R^2 = 0.9727$), supporting the use of the C_T calculations for theoretical well assessment. All C_S and C_T data were strongly correlated for wells 1 and 3, and very well correlated for well 2 ($R^2 = 0.9991$ for wells 1&3; $R^2 = 0.9201$ for well 2). C_T values deviated from C_S for pH, soluble Ca (and, subsequently, Ca:Mg), and Cl for well 2, but were strongly correlated for the other constituents. Despite corrective actions taken during sampling, fluctuations in the pumping rate while sampling well 2 (fluctuations in pumping rate were noticed only in the case of well 2) may have affected flow characteristics and water chemistry, both of which would affect C_T calculations and may possibly explain discrepancies between C_T and C_S data. This potential variability was also observed through differences between the two sample replicates collected from each depth for well 2. The greatest variability was observed from samples collected from the 101- to 109-m bgs depth interval. However, in only one instance did the calculated differences impact whether a constituent was within or beyond the grapevine tolerance threshold: the C_S concentration for Cl of well 2 was measured at 2.48 meq L⁻¹, versus the C_T value of 0.64 meq L⁻¹ (table 1). Although both of these values were below the recommended threshold for grapevine production and irrelevant to overall water quality, this difference affected whether the calculated data in response to a well manipulation increased or decreased for this parameter. Were well 2 to be manipulated, further theoretical analysis may be necessary to verify the effect of a manipulation on overall Cl levels and to verify that additional discrepancies in pH and soluble Ca wouldn't vary more than anticipated.

Profiling of these three wells with known water quality issues demonstrated that the tracer-pulse method could effectively sample and detect slight changes in flow and chemical inputs between the well depths. However, C_a throughout each well's profile was symmetric, with only a few instances of increased concentrations at certain depths. C_a was typically correlated with a zone's overall flow (figs. 2 and 3). Wells 2 and 3 exhibited remarkable similarity in chemical constituents of their profiles, which is a possible consequence of similarities in their proximity, elevation, and geologic parent material (all three wells were located in the Paso Robles Formation- a non-marine geologic formation comprised of sand and gravel layers interbedded with layers of clay and silt). Overall, theoretical analysis indicated that manipulations would do little to improve overall irrigation water quality for any of the wells due to the symmetrical constituent input throughout each well profile, the lack of defined problematic depths, and/or higher chemical inputs generally linked with higher flows at a given depth within each well.

Constituent contributions were relatively symmetrical (i.e., no large spikes in chemical or flow input at any one depth) throughout the depth profile of well 1, limiting the potential benefits that a well manipulation would have on water quality (table 2). Manipulating depth interval 73- to 113-m bgs would address the depth with the greatest percent contribution of all constituents for well 1, and it would create the greatest percent reduction in pH, EC, soluble Ca, Mg, Na, B, Cl, and CO₃. However, the reductions would not adequately lower any constituent below the recommended threshold, and soils irrigated by this well would remain at moderate risk for sodium-related infiltration problems (Hopkins et al., 2007). Blocking all water input at this depth would also result in a prohibitive 41% reduction in overall well flow from 2646 to 1552 L min⁻¹. The large reduction in overall pumping volume combined with limited improvements in water quality would require extensive assessment and consideration based upon usage and demand prior to manipulating the well.

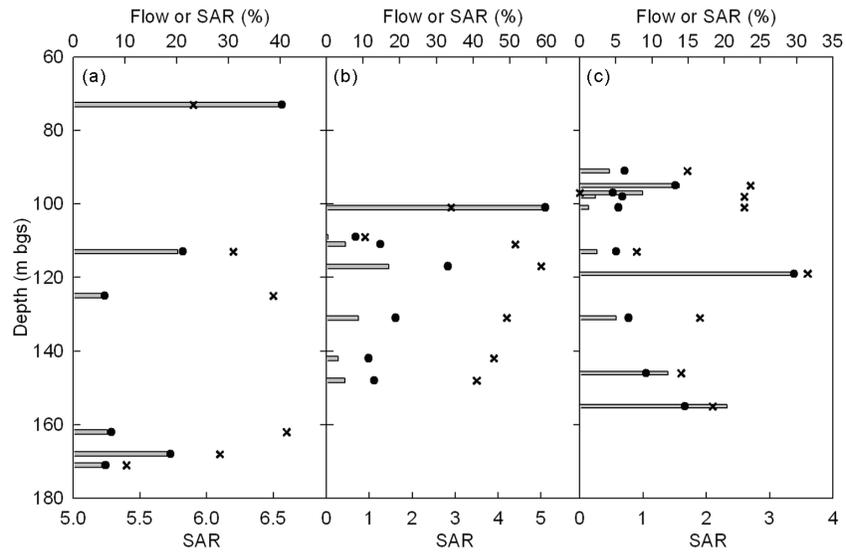


Figure 2. Example SAR and flow profiles for wells 1 (a), 2 (b), and 3 (c) illustrating variations in contribution by depth for this problematic constituent. Percent flow and SAR (horizontal bars and closed circles, respectively) are the percent of the total flow and SAR contribution by the various depths of each well. C_x SAR (x) values are calculated from the absolute data collected from each well depth during tracer-pulse sampling.

A small amount of asymmetry was observed in the overall contribution of a few constituents for well 2 (table 3). Asymmetry in the profile occurred in the 111- to 117-m bgs depth, where concentrations of pH and CO_3 increased and HCO_3 decreased from the symmetrical outputs from the rest of the well. Based upon theoretical assessment, a manipulation would cause the majority of the constituents to increase in concentration (table 3). A manipulation within the 117- to 131-m bgs interval would address the depth with the greatest contribution of nearly all measured constituents and would reduce the concentration of pH, SAR, Cl, soluble B, and CO_3 , yet the concomitant increase in the concentrations of EC, soluble Ca, Mg, and Na, and HCO_3 would negate these positive

effects. In spite of providing only 5.5% of total well flow, a manipulation at 148- to 158-m bgs would alter several constituents with minimal effects on the total flow output. However, weighing reductions to pH, SAR, Cl, soluble B, and CO_3 with increases in EC, soluble Ca, Mg, and Na, and HCO_3 may negate any benefit from a manipulation at this depth. Furthermore, any improvement in salinity may be obscured by a potential increase in risk for sodium-based infiltration problems. The relatively small potential benefit from a manipulation at this depth was unlikely to sufficiently justify the monetary expense of a manipulation. Analysis of the effects of a blockage at other depths yielded some increases and decreases of various parameters, yet overall the effects of a blockage may improve irrigation

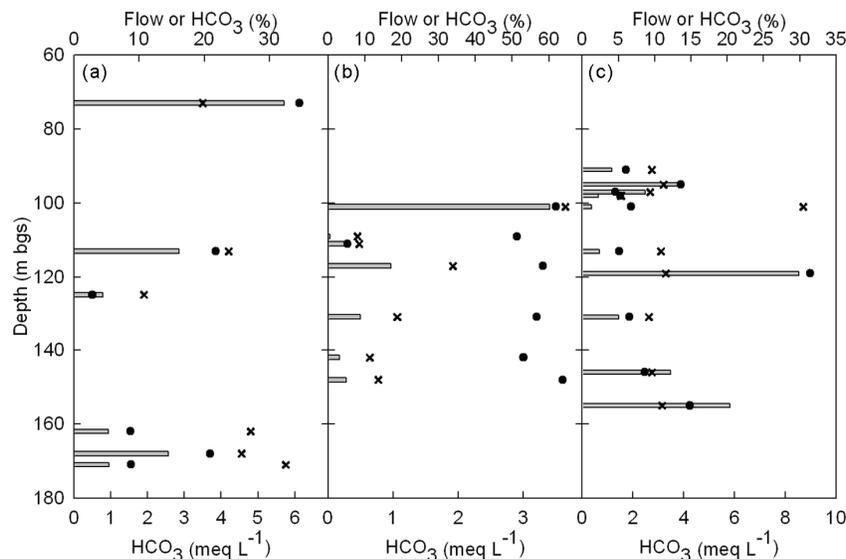


Figure 3. Example profiles for percent flow and HCO_3 for wells 1 (a), 2 (b), and 3 (c) illustrating variations in the problematic constituent contribution by depth. Percent flow and HCO_3 (horizontal bars and closed circles, respectively) are the percent of the total flow and HCO_3 contribution by the various depths of each well. C_x HCO_3 (x, meq L^{-1}) values are calculated from the absolute data collected from each well depth during tracer-pulse sampling.

Table 2. Percent change in calculated water quality (C_T) data following a blockage at each contributing depth interval for well 1.

Depth	pH	EC ^[a]	SAR	Soluble Ca ^[b]	Soluble Mg ^[b]	Ca:Mg	Soluble Na ^[b]	Cl ^[b]	Soluble B ^[b]	HCO ₃ ^[b]	CO ₃ ^[b]	Flow ^[c]
73-113	-0.32	-5.95	-2.25	-4.62	-5.76	-1.05	-4.76	-4.21	-5.76	0.61	-33.13	-41.35
113-125	0.10	3.42	-1.01	-1.31	0.66	-4.14	-0.96	-0.14	-0.39	-1.69	-11.21	-20.68
125-137	-0.05	7.33	-0.50	1.00	0.36	-1.61	-0.16	0.37	0.03	2.55	-5.31	-5.62
162-168	1.51	6.20	-12.2	-0.55	-0.43	-2.35	-0.87	-0.81	-0.46	-2.01	1.79	-6.77
168-171	0.49	9.98	-0.17	-1.39	-0.16	-3.47	-0.45	-0.51	-0.25	-4.04	22.86	-18.61
Original ^[d]	8.48	0.67	6.03	0.66	0.96	0.70	5.42	0.89	0.087	3.97	0.68	2646
New ^[d]	8.45	0.63	5.90	0.63	0.91	0.69	5.16	0.85	0.082	4.00	0.45	1552

^[a] dS m⁻¹.

^[b] meq L⁻¹.

^[c] L min⁻¹.

^[d] Shaded cells show changes in C_T data in response to a blockage in the 73- to 113-m bgs depth interval. Bottom two rows show absolute C_T data based upon a manipulation to the 73- to 113-m bgs depth interval, not percentages.

water concentrations of EC, Ca, Mg, and Na while causing an increase in overall SAR.

Despite some asymmetry in constituent contribution by depth for well 3, theoretical assessment indicated that a manipulation would also be unlikely to improve irrigation water quality for this well, and overall water quality could actually deteriorate in response to a blockage at any depth (table 4). EC, SAR, soluble Na and B, HCO₃, and CO₃ concentrations would increase with a manipulation at any depth. Depth interval 98- to 101-m bgs would have the greatest overall reduction in all constituents, yet changes were minor: pH, EC, Ca:Mg, and Cl would not change more than ±2%. The relatively small change in constituent concentration at this interval may be a partial consequence of this zone only supplying 2.0% of the total well flow in a well displaying consistent concentrations of most constituents throughout the full depth of the well.

The generally symmetrical patterns of constituent contributions measured in the three wells sampled in this study would prevent irrigation water quality from improving in response to a manipulation. A well which would benefit from a manipulation is likely to show a high concentration of constituent contribution from a single depth, ideally in combination with a relatively low water contribution. Manipulating a well with asymmetrical patterns of contamination input with an inflatable packer would be a cost-effective method of improving irrigation water quality particularly for simpler situations where a contaminant needs to be removed in isolation and effects on other quality parameters can be ignored [e.g. reducing nitrate contamination from discrete layers in municipal well

profiles (BESST Inc., 2008)]. Although salinity was the constituent of primary concern for the current study, this method is applicable to other contaminants.

Combining the data resolution provided by the tracer-pulse sampling method with the manipulation capabilities of an inflatable packer make this method a viable option for monitoring and mitigating the effects of asymmetrical constituent contribution in water wells. Although strongly asymmetrical patterns of constituent contribution were not observed in the three wells profiled in this study, use of a well manipulation is a proven technology which would have offered a viable water quality improvement technique if asymmetrical constituent contributions had been observed. Applying these complimentary technologies in agricultural production systems may provide growers with irrigation water improvements without the expense of drilling a new production well under certain circumstances.

CONCLUSION

The tracer-pulse well sampling technique effectively identified the flow and constituent contributions for the full profile of these three wells, with minimal disruption to the well. This sampling technique offered an alternative to more invasive methods while producing a full flow and constituent contribution profile. This method was effective at identifying well intervals with the greatest and smallest salinity and constituent contributions, facilitating theoretical analysis of well manipulation efficacy. Although the constituent contributions of the three wells sampled in this study were too symmetrical overall to benefit from a

Table 3. Percent change in calculated water quality (C_T) data following a blockage at each contributing depth interval for well 2.

Depth	pH	EC ^[a]	SAR	Soluble Ca ^[b]	Soluble Mg ^[b]	Ca:Mg	Soluble Na ^[b]	Cl ^[b]	Soluble B ^[b]	HCO ₃ ^[b]	CO ₃ ^[b]	Flow ^[c]
101-109	4.46	-23.72	31.51	-39.90	-54.75	32.82	-2.73	63.08	2.94	-9.73	38.97	-60.5
109-111	0.21	0.15	2.04	0.24	0.50	-0.25	0.62	0.57	-0.14	0.30	-0.02	-0.5
111-117	-1.05	2.68	0.07	2.25	-23.74	34.08	0.24	-1.64	-18.88	-48.66	203.15	-5.0
117-131	-0.93	5.55	-6.93	10.56	14.36	-3.32	0.97	-5.44	-2.13	1.83	-0.94	-17.0
131-142	-0.56	2.43	-0.60	4.09	5.65	-1.48	0.43	-6.22	-0.33	1.06	-3.94	-9.0
142-148	-0.40	0.95	0.16	1.59	2.20	-0.60	0.17	-2.43	-0.13	0.41	-1.54	-3.5
148-158	-0.56	1.47	-1.91	2.47	3.41	-0.91	0.26	-3.75	-0.20	0.64	-2.38	-5.5
Original ^[d]	8.52	0.83	3.49	1.58	2.12	0.75	4.38	0.64	0.052	3.23	0.87	756
New ^[d]	8.47	0.84	3.43	1.62	2.20	0.74	4.40	0.61	0.052	3.25	0.85	714

^[a] dS m⁻¹.

^[b] meq L⁻¹.

^[c] L min⁻¹.

^[d] Shaded cells show changes in C_T data in response to a blockage in the 148- to 158-m bgs depth interval. Note that bottom two rows show absolute C_T data based upon a manipulation to the 148- to 158-m bgs depth interval, not percentages.

Table 4. Percent change in calculated water quality (C_T) data following a blockage at each contributing depth for well 3.

Depth	pH	EC ^[a]	SAR	Soluble Ca ^[b]	Soluble Mg ^[b]	Ca:Mg	Soluble Na ^[b]	Cl ^[b]	Soluble B ^[b]	HCO ₃ ^[b]	CO ₃ ^[b]	Flow ^[c]
91-95	0.28	1.25	9.40	-0.97	-1.48	0.82	6.85	-1.62	10.29	2.35	18.12	-4.0
95-97	-0.20	1.15	10.61	-1.54	-2.27	1.06	7.77	-1.86	11.51	2.21	21.35	-13.6
97-98	0.03	1.84	12.40	-2.20	-2.62	0.73	9.59	-1.72	13.52	2.40	24.10	-8.8
98-101	-0.04	1.48	8.54	-2.92	-1.84	-0.80	6.47	-0.20	9.42	3.26	1.06	-2.0
107-113	0.00	0.96	8.57	-1.06	-1.48	0.73	6.14	-1.83	9.45	2.07	2.51	-1.2
113-119	0.20	1.15	9.06	-0.86	-1.27	0.72	6.31	-1.64	10.69	2.27	30.39	-2.4
125-131	0.62	1.21	7.17	6.96	5.35	1.84	5.11	-1.39	8.04	2.39	11.45	-30.0
137-146	0.36	1.34	8.82	-0.63	-1.02	0.70	6.43	-1.44	9.71	2.47	16.38	-5.2
146-155	0.25	1.05	7.95	-0.71	-1.01	0.61	5.69	-1.66	8.83	2.19	14.28	-16.0
Below 155	0.07	0.86	7.72	-0.88	-1.17	0.48	5.46	-1.84	8.60	2.00	13.97	-16.4
Original ^[d]	8.33	0.70	2.29	1.74	1.91	0.91	3.07	1.79	0.031	3.07	0.46	945
New ^[d]	8.32	0.71	2.49	1.69	1.87	0.90	3.27	1.78	0.034	3.17	0.47	926

^[a] dS m⁻¹.

^[b] meq L⁻¹.

^[c] L min⁻¹.

^[d] Shaded cells show changes in C_T data in response to a blockage in the 98- to 101-m bgs depth interval. Note that bottom two rows show absolute C_T data based upon a manipulation to the 98- to 101-m bgs depth interval, not percentages.

well manipulation, the tracer-pulse method and theoretical analysis can effectively be combined to identify whether a well manipulation would reduce zonal contamination and improve irrigation water quality for a well with more asymmetrical contamination contribution patterns. These tools can be useful to vineyard managers and other agricultural producers who are experiencing poor water quality from irrigation wells which display an asymmetrical pattern of constituent supply to the well, such as those pumping from a contaminated aquifer. Assuming an acceptable amount of flow reduction, combining the tracer-pulse sampling method with a manipulation such as an inflatable well packer can offer growers an affordable alternative to installing a new production well in response to poor water quality. Additional research may pair known aquifer data, such as those affected by salinity or salt-water contamination, with well logs to increase the overall understanding of each well's contributions zones, ultimately improving the probability of identifying asymmetrical contamination patterns and the potential for the tracer-pulse technology to identify well sections that could benefit from a well manipulation.

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