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## Estimating agricultural deep drainage lag times to groundwater: application to Antelope Valley, California, USA

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### Abstract:

Estimates of groundwater volumes available in semiarid regions that rely on water balance calculations require the determination of both surface to groundwater lag times and volumes from irrigation or rainfall initiated recharge. Subsurface geologic material hydraulic properties (e.g. hydraulic conductivities, water retention functions) necessary for unsaturated flow modelling are rarely available as are the instrumented field tests that might determine such lag times. Here we develop a simple two-parameter (specific yield,  $S_v$ , and pore-size distribution index,  $\lambda$ ), one-dimensional unsaturated flow model from simplifications of the Richards equation (using the Brooks-Corey relationships) to determine lag times from agricultural deep drainage associated with the irrigation of alfalfa hay and various row crops in the Antelope Valley of California, USA. Model-predicted lag times to depths of 85 m bgs were similar to that measured in a 2-year ponded recharge field trial, slightly overestimating that measured by approximately 15% (0.51 vs 0.44 years). Lag time estimates were most sensitive to estimated deep percolation rates and roughly equally sensitive to the model hydraulic parameters. Generally, as subsurface material textures coarsen towards larger  $S_{\rm v}$  and  $\lambda$ values for all  $S_v > 10\%$ , lag times progressively increase; however, at  $S_v < 10\%$ , lag times decrease substantially suggesting that particular combinations of  $S_v$  and  $\lambda$  values that may be associated with similarly textured materials can result in the prediction of different lag times for  $S_y$  approximately 10%. Overall, lag times of 1–3 years to a depth of 69 m bgs were estimated from deep drainage of agricultural irrigation across a variety of irrigation schedules and subsurface materials. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS unsaturated flow; soil water retention; water balance; deep percolation; evapotranspiration; depth to groundwater

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#### INTRODUCTION

As reliance on groundwater resources increases in arid and semiarid regions, water balance estimates of aquifer recharge and pumping are critical towards the determination of long-term groundwater availability (i.e. safe or sustainable yield). The closure of the water balance calculations requires the determination of the recharge (e.g. basin rainfall, irrigation and stream seepage) rates, volumes and lag times to reach aquifers of interest at depth. It is critical to water resources planning both locally and across broad regions (Sophocleous, 2005). Nowhere has this determination been more crucial towards the allocation of water resources then in the arid Antelope Valley located approximately 64 km northeast of Los Angeles, California,

F1 USA (see Figure 1).

As will be discussed in the next section, there are several groundwater recharge estimation methods from which lag times to groundwater at depth are determined. These methods typically rely on field measurements of subsurface water contents, matric potentials, environmental (e.g. chloride) and stable isotope tracer concentrations and changing water table elevations to indirectly assess the relatively slow movement of surface recharge or deep drainage. The soil water hydraulic properties of the subsurface geologic materials necessary for unsaturated flow modelling are rarely available as are the instrumented field tests that might determine such lag times. Several studies have underscored that the estimated lag times depend particularly on the subsurface unsaturated hydraulic properties, parameters for which are extremely difficult and expensive to measure in the field. Here, a somewhat different approach is taken that couples a surface soil water (root zone) balance model to determine average daily deep percolation (DP) rates from irrigated crops with a simple one-dimensional unsaturated flow model to estimate lag times and cumulative recharge to groundwater at depth. The two-parameter unsaturated flow model relies only on driller-log-type information for parameterization. The application of the model is demonstrated through comparison with field-measured lag times to depth and estimation of agricultural deep drainage lag times to groundwater in the Antelope Valley of southern California, USA.

### STUDIES OF RECHARGE RATES AND LAG TIMES TO GROUNDWATER

Analyses of lag times and recharge rates to deep groundwater have been the subject of several investigations dating back at least six decades (Hvorslev, 1951), with periodic reviews of techniques and observations in the following decades (e.g. Gee and Hillel, 1988; Jolly

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Figure 1. Alfalfa hay production study area considered in the Antelope Valley, California, USA

et al., 1989; Scanlon et al., 2002; Cook et al., 2003) as concerns about possible contamination and available water supply increased. Of course, this problem is not new and has been considered in terms of available water resources around the world (e.g. in Pakistan by Hendrickx et al., 1991; Central Plains, USA, by Sophocleous, 2005; Central Australia by Harrington et al., 2002) and more recently by anticipated climate change effects on recharge (e.g. Scanlon et al., 2005; Gurdak et al., 2007). Similarly, concerns about the timing associated with migration from salinity and contaminant affected near-surface soils to usable groundwater also rely on estimates of recharge rates and times to water table aquifers (e.g. Jolly et al., 1989; Jolly & Cook, 2002; Cook et al., 2003). Deep groundwater recharge in semiarid and arid regions is complicated by the thickness and properties of the vadose zone, changes in land-use conditions (e.g. conversion of dryland forests to pastures or desert areas to irrigated crops) and the episodic nature of recharge from excess winter rainfall in nonirrigated areas as compared with the diffuse recharge from irrigated areas. Scanlon et al. (2002) provided a comprehensive review of the most commonly deployed measurement techniques for the estimation of groundwater recharge rates and underscores that in many cases multiple approaches should be taken as each develops different results and only ranges of groundwater recharge rates or lag times can be provided. T1 Table I summarizes results of several recent groundwater recharge rate studies to provide some context for the following discussion.

Groundwater recharge occurring in dryland agricultural regions is evidenced by increases in water table elevations, downward total potential gradients approaching unity and low chloride concentrations in the unsaturated zone. Original estimates of groundwater recharge rates in agricultural areas depended on measurements of water table elevation fluctuations and computation of Darcian fluxes using measurements of subsurface material hydraulic properties. For example, Rehm et al. (1982) determined groundwater recharge rates in the northern plains (North Dakota, USA) and compared Darcian-flux estimates with that from water table fluctuations. They found Darcian-flux recharge rates to be ten times greater than that estimated from water table fluctuations and that rates through 'sandy material' were also ten times greater than those in 'fine-textured material'. On the basis of stable isotope analyses, estimated recharge rates of 10-40 mm/year or 2.5%-10% of precipitation occurred mostly because of spring snowmelt and only occasionally from late fall thunderstorms and that greater recharge occurred from sloughs where surface water accumulated as compared with the plains. These results were consistent with later studies suggesting recharge rates of approximately 4% of precipitation deduced from groundwater modelling and approximately 5% estimated by Scanlon et al. (2005) using tracer methods.

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Table I. Brief summary of recent semiarid and arid agricultural region groundwater recharge (RC) study results

Location	Land use	RC method	Vadose-zone materials	Rain (R) or AW (mm/year)	Recharge rate (mm/year)	References
Murray Basin,	Eucalyptus woodland	MP, MC and CMB	Sandy soils, little clay	~370 (R)	0.05-0.2	Jolly et al. (1989)
South Australia	Dryland pasture				3-45	
Murray Basin,	Eucalyptus woodland	CMB and EM	Sand to sandy loam	340 (R)	0.04-0.06	Cook et al. (1989)
South Australia	Dryland pasture				3-60	
Amargosa Desert,	Alfalfa hay production	CMB and STP	Sands to sandy loams	2000–2700 (AW)	130-640	Stonestrom et al. (2003),
Nevada, USA	River channel			113 (R)	2-150	Scanlon et al. (2005)
South High Plains, USA	Dryland agricultural region,	MP, CMB and STP	Clays, silts, sands	~465 (R)	9–31 (dryland), 0.5–2 (range),	Scanlon et al. (2005),
	rangeland, irrigated		and gravel		130-200 (irrigated agriculture)	McMahon et al. (2003),
Central High Plains, USA	agriculture			~550 (R)	5-54	McMahon et al. (2006)
North High Plains, USA				~700 (R)	17-111	
Ti-Tree Basin,	Native shrub	CMB, STP	Medium to coarse	290 (R)	0.1–2.8	Harrington et al. (2005)
Central Australia			sandstones			
Walnut Creek,	65% cropland 35% range	GW model	Silt to clay loams	510-660 (R)	1-406 48 (36-year average)	Ramireddygari et al. (2000)
Kansas, USA	and pasture					
Finney County,	Irrigated agriculture,	MP	Silt to clay loams	~550 (R)	0.5-3 (irrigated agriculture),	Sophocleous (2005)
SW Kansas, USA	natural grassland				0.1 - 0.25 (grass)	
Central Coast,	Avocado/citrus orchard	MC, CMB and SWB	Silty clay loams	394 (R) 442 (AW)	75 (SWB, 15 years),	Grismer (2000),
California, USA					164 (SWB, 2 years),	Grismer et al. (2000)
					141–232 (CMB),	
	Dryland orchard			394 (R)	180 (MC, 2 years) 7–42 (CMB), 189 (MC, 2 years)	

AW, applied water; EM, electromagnetic induction (Geonics EM34); MC, moisture content profiles; MP, matric potential profiles; STP, stable tracer profiles; SWB = soil water balance method.

### ESTIMATING AGRICULTURAL DEEP DRAINAGE LAG TIMES TO GROUNDWATER

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have focused on the effects on land-use conditions on groundwater recharge rates, including conversion of native range or woodlands to irrigated or dryland farming. In Australia, the conversion of eucalyptus woodlands (mallees) to agriculture resulted in much greater recharge rates over historical conditions on the basis of chloride mass balance (CMB) and matric potential profile techniques (e.g. Cook et al., 1989; Allison et al., 1990; Walker et al., 1991). Similarly, in the central Great Plains and southwest desert regions of the USA, conversion to agricultural production increased recharge rates and decreased water table depths (e.g. Stonestrom et al., 2003; and Scanlon et al., 2005). Increased recharge in dryland farmed areas may be attributed to fallow periods in combination with increased permeability of surficial soils because of plowing. The importance of fallow periods was shown in the Northern Great Plains, USA, by reduced recharge when crop-fallow rotations were replaced by perennial alfalfa in experimental plots. Fallow periods were also shown to increase soil water storage and drainage compared with Q3 continuous cropping in Australia (O'Connel et al., 2003). Cultivated fallow soils are not subject to the water losses associated with native rangeland vegetation areas where soil drying occurs in spring (Scanlon et al., 2005). Such changes in land use that result in increased deep drainage create a pressure front that moves down through the soil towards the water table (Jolly et al. 1989). Until the pressure front reaches the water table, aquifer recharge continues at the same rate as it did before agricultural development. When the pressure front reaches the water table, aquifer recharge increases, causing the water table to rise. This time lag between the increase in deep drainage and the increase in aquifer recharge is related to the deep drainage rate, the initial water table depth and the soil water content within the unsaturated zone. Time lags for agriculturally induced recharge associated with land conversion in arid or semiarid regions to reach groundwater have been typically estimated to be in the decades to a century time scales (Sophocleous, 2005).

In the past 2–3 decades, groundwater recharge studies

Although the application of irrigation water might be expected to dramatically increase groundwater recharge rates as compared with nonirrigated agricultural production, this has not always been the case. In a long-term central USA study (rainfall of 448-623 mm/year), Dugan and Zelt (2000) reported that irrigated production increased recharge rates a few millimetres per year over nonirrigated conditions and that recharge rates from alfalfa hay production were the lowest (as compared with corn, soybeans and sorghum) at 1-3 mm/year whether irrigated or not. Similarly, using soil water balance (SWB), CMB and soil moisture profile techniques, Grismer et al. (2000) found that micro-irrigated citrus/avocado orchards on the central California coast USA developed a groundwater recharge rate that was slightly less than nonirrigated bare areas of the ranch. A 15-year SWB analysis (1984-98) provided insight into the groundwater recharge process being driven by winter rains rather than summer irrigation and indicated an average rate of 75 mm/year. The application of the CMB method to estimate recharge rates from the orchards was difficult because of the unusually high, variable soil water chloride concentrations. Contrary to that expected, chloride concentrations at depth in the nonirrigated soil profiles were greater than that in the irrigated profiles despite far smaller chloride input, although this observation suggested possible greater leaching of the irrigated soil profiles. The CMB orchard recharge estimate of 141 mm/year was nearly twice that of the SWB 15-year average. Having access to the long period of record was important because it encompassed both drought and heavy rainfall years. In the nonirrigated areas, the CMB method seemed to underestimate annual recharge by more than ten times, perhaps because of the marine terrace environment of the ranch. Direct and continuous soil moisture monitoring for the 2-year (1996–98) period was necessary to identify both short-term (daily) and seasonal seepage processes to corroborate recharge estimates from the other two methods. The measured recharge rate during this period in the orchards was 180 mm/year (as compared with the SWB estimate of 164 mm/year) whereas that in the nonirrigated site was 189 mm/year, not significantly different. Previous soil moisture measurements indicated that the irrigation water wetting front penetrated to depths of less than a metre within 1 day after irrigation and then a 'drying front' moved towards the soil surface within the next 2-3 days (Grismer, 2000). As a result, the overall soil profile showed a net decline in soil moisture to depths in excess of 3 m between irrigation events and during the irrigation season as a whole. In contrast, within several days after rainfall events greater than roughly 20 mm, soil moisture contents increased to depths of approximately 2 m, and the overall soil profile moisture content progressively increased throughout rainy periods. The rainfallinduced peak or 'pulse' reached depths of roughly 5 m within 2 months after significant rains in the irrigated avocado soil profile and within 6 months in the nonirrigated profile. The pattern of soil profile drying during the summer irrigation season followed by progressive wetting during the winter rainy season was observed in both irrigated and nonirrigated soil profiles, confirming that groundwater recharge was rainfall driven and that micro-irrigation did not increase excess rainfall recharge (Grismer et al., 2000). Moreover, the relative speed of the rainfall recharge wetting front, reaching depths of 5 m within a few months, suggested that lag times to groundwater at depths of 35 m may occur in less than 2 years at the ranch.

In contrast, the conversion of desert rangeland to alfalfa hay production in the southwest desert of Nevada, USA, resulted in far greater recharge rates as compared with drychannel and native desert conditions (Stonestrom et al., 2003). Recharge rates determined using the CMB method in native desert areas were miniscule, resulting in rainfall recharge lag times to groundwater on the order of millennia, whereas those rates in the dry-channel ranged from 20 to 150 mm/year and those in agricultural areas were far greater. Below irrigated alfalfa hay production fields where water application rates were estimated to be 8-9 mm/day for approximately 300 days/year, annual average recharge rates

of roughly 1 mm/day resulted through the sandy subsurface materials. They estimated that this seepage loss represented roughly 8%-16% of the applied water, a fraction similar to that estimated from the dry-channel flows. Interestingly, Scanlon et al. (2005) found a similar recharge fraction of approximately 12.5% from a range of applied water plus rain conditions across the Great Plains, USA (see Figure 14 of Scanlon et al., 2005). CMB estimated seepage velocities in the Nevada study ranged from 0.1 to 5 m/year, suggesting that lag times to groundwater at 35 m depth were on the order of decades, averaging approximately 30 years for the irrigated areas. As noted earlier by Cook et al. (1989), Stonestrom et al. (2003) attributed spatial variability in estimated groundwater recharge rates to primarily nearsurface seepage rates (irrigated > channel > native areas) and heterogeneity of the subsurface sandy materials. Outside of natural surface depressions or channels and irrigated or dryland farmed areas where recharge rates can readily span two orders of magnitude (i.e. 1-100 mm/year, see Table I), spatial variability concerns diminish as recharge rates in 'undisturbed' natural areas of arid and semiarid regions are quite small (i.e. <0.1 mm/year).

Although often hampered by lack of subsurface materials, hydraulic data, unsaturated or vadose-zone modelling has been used to estimate deep drainage rates and possibly lag times below the root zone under a range of conditions usually with the goal of evaluating the relative impacts of various factors on calculated rates. Scanlon et al. (2002) summarized the variety of approaches used to simulate unsaturated flow, including soil water storagerouting approaches, quasi-analytical approaches and numerical solutions to the Richards equation. As noted in previous studies suggesting the use of multiple methods, they caution that theoretically the range of recharge rates that can be estimated using numerical modelling is infinite and that the reliability of these estimates should be checked against field information. Because of the large ranges of field and laboratory-measured hydraulic conductivities and the nonlinear relationships between hydraulic conductivity and matric potential or water content, recharge estimates on the basis of unsaturated zone modelling that use the Richards equation may be highly uncertain. Daily time steps are desirable for the estimation of recharge because recharge is generally a larger component of the water budget at smaller time scales (Scanlon et al., 2002). Models can play a very useful role in the recharge estimation process, including the determination of sensitivity of recharge estimates to measured or estimated parameters. Nonetheless, the determination of groundwater recharge rates and lag times to groundwater supplies at depth remains an iterative process that includes model and estimate refinement as additional information is developed.

#### **RESEARCH OBJECTIVES**

The overall goal of this research was to develop a coupled root zone–vadose zone methodology for determining average travel or lag times of agricultural root zone drainage (otherwise called DP or drainage) through thick (tens of metres) vadose zones from very limited subsurface hydraulic data in arid and semiarid regions. The particular application of this work is in the Antelope Valley, California, where water table depths are typically 70-100 m in agricultural areas and available water supplies are currently contested. Accomplishing this goal required two parts: (i) the determination of likely daily DP rates from agricultural production and (ii) the development of a simple vadose-zone flow model. As only driller-log descriptions of subsurface material properties was available, the unsaturated flow model or equations required needed to be simple and readily parameterized from driller-log information. The research hypotheses were directed by elucidating the factors affecting determinations of available water supplies in arid and semiarid regions under irrigated agricultural production and included the following:

- 1. Although groundwater recharge in arid regions is typically episodic because of infrequent rain or periodic irrigation events (Gee & Hillel, 1989; Harrington *et al.*, Q4 2002), the average daily DP across 7- to 14-day periods Q5 has little to no effect on the estimated lag times to groundwater at depths of approximately 70 m.
- 2. Irrigation-related DP volumes are not singular recharge events to groundwater but rather continuous with recharge rates increasing and decreasing potentially out of phase with near-surface DP rates.
- 3. At typical irrigation-related DP rates, subsurface clay layers do not increase estimated lag times because at relatively large matric potentials, clay soil hydraulic conductivity likely far exceeds that of much coarser sandy soils.

The specific project objectives considered here included the following:

- 1. to develop average daily irrigation DP rates from production of alfalfa hay and carrot–potato rotations in the Antelope Valley, California, USA;
- to develop simple unsaturated flow equations/model capable of determining lag times of DP from item 1 to groundwater at depths of approximately 70 m for typical valley subsurface profiles; and
- 3. to evaluate model prediction sensitivity to driller-log information, seepage rates and depths to groundwater.

#### PROJECT SETTING

The Antelope Valley is bounded on the south and west by the San Gabriel and Tehachapi Mountains, respectively, on the north by the Rosamond and Bissell Hills and on the east by the buttes and alluvial fans of the Hi Vista area. Fremont Valley is located to the north, and just to the east is Victor Valley where field measurements of lag times (Izbicki *et al.*, 2008) were conducted. The Antelope Valley is a closed basin of approximately 346,000 ha with surface elevations that range from 700 to nearly 1100 m m.s.l. It is composed of relatively flat valley land and dry lake beds with coalescing alluvial fans and scattered buttes around the periphery. The near-surface (<100 m bgs) quaternary alluvial deposits across the valley are generally coarse materials (sands to gravels), including layers of sands with interbedded silts and clays and some relatively thin silt/clay layers (e.g. see Dibblee, 1967; Ponti, 1985). Several creeks drain the surrounding mountains, most notably perennial Big Rock and Little Rock Creeks, cross the alluvial fans generally dissipating into dry washes in the valley. Agricultural lands are spread across the area surrounding the valley urban centres (e.g. Lancaster, Palmdale) and Edwards US Air Force Base, historically exceeding some 25,000 ha decreasing to just more than 10,000 ha currently.

Antelope Valley climate is dry with typically less than 250 mm of average annual rainfall while the surrounding mountains receive upwards of 460 mm annually, with the great majority occurring during the winter months from November through March. Valley temperatures vary greatly by day with highs exceeding 38 °C in the summer months and lows below freezing in the winter months, while average monthly temperatures range from approximately 6 °C in January to 31 °C in August. As a result, the average length of the growing season for most of the valley is 215 to 245 days/year, generally from April through October. High wind speeds across the valley create erosion problems of blowing soil and accumulation of wind-driven sand on irrigated lands as well as advecting drier air contributing to higher evaporation and crop water demands (consumptive evapotranspiration, ET<sub>c</sub>) than otherwise associated with such area temperatures.

Historically, Antelope Valley has been recognized for continuous cropping of alfalfa hay, a year-round crop often grown in 4–5 year cycles in southern California desert regions. More recently, the production of vegetable crops including carrots, potatoes and onions grown in rotations with winter wheat or barley has become more common across the valley. This analysis considers the likely irrigation schedules for surface or sprinkler irrigated alfalfa hay production and carrot–green chop–wheat or potato–green chop–wheat rotations in the valley on the basis of root zone water balances for 10-year averaged  $ET_c$  conditions determined from recent California Irrigation Management and Information System (micrometeorological stations) data available in the valley. From the water balance calculations, root zone seepage lag times required to reach hypothetical groundwater at a depth of 69 m bgs for a range of subsurface geological conditions found in the valley are determined.

#### VADOSE ZONE SEEPAGE MODELLING

The lag time required for irrigation DP water to reach a specified depth depends on the application frequency, subsequent root zone DP rates and subsurface soil water hydraulic characteristics (related to soil textures and bulk densities) and depth of interest. Here, the Richards equation for one-dimensional vertical soil water transport is used assuming Green-Ampt or 'square wave'-type seepage water content profiles with time and depth following the approach of McWhorter and Nelson (1979). This equation is solved using a variable time step and assuming successive quasi-steady-state conditions, possible because of the very small soil water fluxes associated with root zone DP rates on a daily and annual basis. Flow below the root zone is assumed to be at capillary pressure heads (i.e. matric suctions) greater than the substrata displacement pressure heads,  $h_d$ , typically small values for coarse sandy subsurface materials encountered in the Antelope Valley. When solving the Richards equation for the lag times to depth, the resulting equations can be simplified such that the parameter requirements for this model are few, a major advantage of this approach considering the lack of soil water hydraulic parameter availability for the valley substrata. By way of a summary, the key parameters required in the unsaturated flow model are summarized and described in Table II.

Considering vertical seepage, q, through a nondeforming porous media layer f of thickness  $L_{\rm f}$  and hydraulic conductivity K<sub>i</sub>, the Darcy equation can be written as

$$q_{\rm f} = K_{\rm f}(\delta H/L_{\rm f}) \tag{1}$$

where  $\delta H$  is the change in piezometric head across the layer, a value that depends on the capillary and gravity driving forces. As in saturated flow regimes, in

Table II. Summa	ry of unsaturated	d flow equation	parameters	used in the	vadose zone	modelling (a	see Grismer,	1986)
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Parameter description	Symbol	Normal range	Modelled values	Comments
Initial volumetric water content	$\theta_{i}$	0-0.4	$\theta_{\rm r}$	Substrata assumed near dry or gravity drained
Residual volumetric water content	$\theta_{\rm r}$	0.05-0.2	ŇA	Gravity-drained value
Maximum volumetric water content	$\dot{\theta_{m}}$	0.3-0.45	NA	90%–95% of porosity
Specific yield (%)	Sv	3–25	$(\theta_{\rm m} - \theta_{\rm r}) \times 100$	Estimated from driller-logged soil textures
Displacement pressure head (mm)	$h_{\rm d}$	50-900	NA	Measure of largest interconnected pore size.
• • • •	u			Vadose flow assumed at $h_{\rm c} > h_{\rm d}$
Saturated hydraulic conductivity (m/day	) $K_{\rm s}$	Orders of magnitude	0.06-12	Depends on $h_{\rm d}$ ; here determined from $S_{\rm v}$
Pore-size distribution index	λ	1–5	1–3	1 = broad pore-size range to
				5 = near singular pore size

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unsaturated seepage at long times and/or very slow rates, the seepage rate through a particular layer is controlled by gravity rather than capillary forces such that the gradient approaches one and

$$q_{\rm i} \to K_{\rm f}(q_{\rm f})$$
 (1)

that is, the unsaturated hydraulic conductivity associated with the average water content,  $\theta_{\rm f}$ , behind the seepage wetting front. Using the Brooks–Corey expressions relating the porous media water content, capillary pressure head and hydraulic conductivity, the capillary pressure head,  $h_{\rm f}$ , within the layer can be determined from

$$K_{\rm f}(q_{\rm f}) = K_{\rm sf}(h_{\rm d}/h_{\rm f})^{(2+3l)}$$
 or  $h_{\rm f} = h_{\rm d}(K_{\rm f}/q)^{1/(2+3l)}$  (3)

Similarly, the layer average water content associated with the seepage rate is given by

$$q_{\rm f} = (q_{\rm m} - q_{\rm i})(q/K_{\rm f})^{{\rm l}/(2+3l)} + q_{
m e}$$
 (4)

Setting the initial water content at the residual value,  $\theta_r$ , as a minimum, then the drainable porosity or specific yield  $S_y = (\theta_m - \theta_r)$ . With this substitution for  $S_y$ , Equations (1), (3) and (4) can be combined to eliminate  $\theta_f$  and solved for the time required for seepage to pass through the layer

$$t = (S_{y}L_{f}/q)(q/K_{sf})^{l/(2+3l)}$$
(5)

Using the  $S_y$  values assigned to each subsurface material by layer, the  $K_s$  of that layer can be determined from the USBR Drainage Manual relationship between  $S_y$ and  $K_s$  (USBR, 1993), thereby resulting in a relationship that depends only on the DP rate, the layer thickness,  $\lambda$ and  $S_y$  values. The model computes the time required for the wetting front associated with daily recharge (DP) to pass through each layer *en route* to any desired depth at or above groundwater.

The required unsaturated flow model information about the shallow aquifer hydraulic characteristics was estimated from the driller-log information and the  $S_y$  values assigned to each log classification (e.g. sands, clays, etc.). Relative to the parameters outlined in Table II, uniform-grained sands generally have large  $K_s$ ,  $S_v$  and  $\lambda$  values with small  $\theta_r$ and  $h_d$  values. In contrast, clay loam-like materials are characterized by small  $K_{\rm s}$ ,  $S_{\rm y}$  and  $\lambda$  values with larger  $\theta_{\rm r}$ and  $h_{\rm d}$  values. The unsaturated flow hydraulics are controlled in part by the porous media  $\lambda$  values for which a value of two has often been adopted for most agricultural loam soils and has an otherwise theoretical basis from pore-channel hydraulic considerations (see discussion of  $\lambda$  by Grismer, 1986). All  $\lambda$  values at three or larger are effectively equivalent and are associated with sandy materials having a very narrow pore-size distribution and potentially large  $S_{\rm v}$ . Flow in unsaturated soils is somewhat counterintuitive in that fluxes are more limited, or rates can be much smaller in sands as compared with say clay loams

at equivalent capillary pressure heads greater than  $h_d$  of the sand because of orders of magnitude smaller unsaturated hydraulic conductivities in the sand.

#### MODEL COMPARISON WITH FIELD STUDIES

Izbicki *et al.* (2008) conducted a seepage study west of Victorville on the Oro Grande River wash area to determine deep seepage lag times from ponded water. After removing the topsoil, they encountered primarily three geologic-type units during test drilling below the ponded area: alluvium reworked from the Victorville Fan, Victorville Fan deposits and ancestral deposits of the Mojave River.

Alluvium reworked from the Victorville Fan deposits consists of permeable sand approximately 6.4 m thick overlain by soil. A basal gravel unit was present at the base of the reworked alluvium. The Victorville Fan deposits consisted of silty sand, with smaller amounts of silt, clay and gravel interspersed throughout the deposits (Izbicki et al. 2000) and contained abundant fragments of Pelona Schist eroded from the San Gabriel Mountains. A clay-rich paleosol, more than 1 m thick, was present at the top of the Victorville Fan underlying the reworked alluvium at approximately 6 m below land surface. Excluding the overlying soil, this clay layer was the shallowest impediment to the infiltration of water at the site. Thinner, clay-rich paleosols were encountered at greater depths throughout the Victorville Fan deposits. The Victorville Fan deposits were more consolidated and less permeable with depth. Ancestral Mojave River deposits, consisting of highly permeable sand similar in appearance to sand along the present-day Mojave River, were encountered just above the water table approximately 111 m below land surface.

In this field study, they measured initial water contents  $(\theta_i)$  that ranged from 0.02 to 0.34 with a median of 0.16, porosities ( $\phi$ ) that ranged from 0.21 to 0.41 with a median of 0.30, and a large median dry bulk density of  $1850 \text{ kg/m}^3$ . Similarly, saturated hydraulic conductivities ranged from 0.002 to 0.57 m/day with a median of 0.16 m/day. These ranges and median values are similar to that found in the Antelope Valley and indicate that initial water contents in the field, although low, are greater than residual values on average. Similarly, the relatively large median  $K_s$  value reflects the coarse nature of the subsurface materials. The very small  $K_s$  value was found in a dense clay layer approximately 10 m bgs that became the limiting layer for deep seepage rates from the ponded water. In their initial assessment, they used a measured average pond seepage rate of 0.6 m/day but found that this value resulted in untenable model predictions at depth. The presence of the dense clay layer increased lateral spreading subsurface and restricted vertical flows to a seepage rate of approximately 15 mm/day. To test the use of the seepage equations outlined earlier, we simplified the subsurface logging information described earlier and developed by Izbicki et al. (2000) below the 10-m deep dense clay layer. They

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found gravelly sands to sandy gravels eventually fining to silty sands at depth that were modelled here as a single unit of simple fine sand with  $\lambda = 3$  and  $S_v$  ranging from 10% to 15%. The ponded recharge periods from October 2002 to September 2003 were punctuated by two approximately 48-day periods of limited flooding, resulting in assumed steady recharge occurring for 81, 41 and 147 days. From their lysimeter/tensiometer measurements at a depth of approximately 85 m, they determined the arrival of the main seepage pressure 'pulse' to be approximately 0.44 years, a value approximately 15%-24% less than the 0.51–0.58 years estimated here using the simplified subsurface profile. This overestimation in lag times is well within the range of estimated recharge rates used by Izbicki et al. (2008). It results in pressure to solute wetting front speed ratios of 0.75-0.86 that are greater than the 0.33suggested by Jolly et al. (1989), which would imply that the wetting front-based time lag estimate should be approximately 0.9 years. This discrepancy may also reflect the use of the simplified subsurface profile rather than a more complexly graded profile as described by Izbicki et al. (2000).

A similar model comparison, although with less information, was conducted using the estimated root zone drainage rates of 100-200 mm/year from alfalfa hay production in Nevada by Stonestrom et al. (2003). Subsurface profiles below the alfalfa production root zones ranged from medium to coarse sands to approximately 10 bgs and then fine sands thereafter with interspersed siltyclay lenses to water tables at depths of approximately 35 m. Assuming an average DP rate of 150 mm/year and simplified profile average values of  $\lambda = 2.2$  and  $S_v = 18\%$ , the estimate of DP lag times to 35 m bgs on the basis of Equation (5) was 4.2 years, a value roughly seven times less than the 30-year average from the range of 11–70 years that Stonestrom et al. (2003) estimated on the basis of environmental tracer (e.g. CMB) methods. As discussed earlier, such estimates, however, are heavily dependent on the assumed or estimated DP rates near surface (unmeasured in this case). Nonetheless, the simplified approach developed here seems to compare reasonably with measured values and satisfactorily estimate recharge lag times to groundwater in the Antelope Valley within the same ranges of estimates developed by the studies summarized in Table I.

#### IRRIGATION DEEP PERCOLATION ESTIMATION

Alfalfa hay water use efficiency (WUE) in the Antelope Valley during the past two decades is consistent with that of neighbouring desert regions of southern California. In F2 this comparison shown in Figure 2 (and Grismer, 2001), WUE is based on annual crop water demand being conservatively (over)estimated as equivalent to 100% of net ET (i.e. daily reference ET (ET<sub>o</sub>) less effective rainfall) and county hay production records. That average desert alfalfa production WUEs across the region suggests that an irrigation schedule similar to that used in neighbouring counties is reasonable for modelling daily rates of root zone DP losses to deep groundwater in the valley. Here, daily DP, or recharge below the alfalfa root zone (1.5 m thick soil profile), was determined from daily SWB calculations presuming full stand establishment and crop coefficients as described in FAO-56 (1998). A similar set of calculations were developed for the irrigation of carrot–chop–wheat and potato–chop–wheat rotations in which the active root zone depth increases from a minimum of 50 mm to a maximum of 600 mm as the crop matures. Irrigation schedules developed from the SWB were verified by local growers as typical of their irrigation management on average.

Root zone SWB calculations rely on net ET, changes in soil water storage and the management assumption that irrigation is required when soil water storage falls to <30% of capacity. Net ET was determined from historical micrometeorological data available for the valley (California Irrigation Management and Information System stations) and neighbouring regions. Soil water holding capacity of the crop root zone was taken from soils surveys (by USDA National Resources Conservation Service) and assumed to apply across the entire 1.5m soil profile in the case of alfalfa hay production and across a 50- to 600-mm thick profile for the vegetable/ grain production rotations. Although the daily SWB indicates a single recharge event on the day of irrigation, such instantaneous recharge is unlikely. Both field and theoretical subsurface drainage studies indicate that root zone seepage rates decrease exponentially after surface irrigation events. Although such variable DP rates are briefly considered here for hypothesis testing, the focus here is on the more conservative (in terms of greater lag times required for DP water reach groundwater at depth) constant DP rates between irrigation events. Thus, daily root zone DP was assumed to occur at an average rate of the irrigation day DP event divided by the number of days between irrigations events. As an example, Figure 3 F3 illustrates the averaged daily DP seepage rates during the year from alfalfa hay production at the different application efficiencies (AE = Net ET/applied water), and Figure 4 illustrates the variation in daily seepage F4 rates assuming more instantaneous recharge with exponential decay after an irrigation event for the one AE case. Note that the averaged DP rates (Figure 3) range from approximately 0.5 to 3 mm/day (similar to the ~1 mm/day estimated by Stonestrom et al., 2003) whereas instantaneous rates can be ten times greater (Figure 4).

Agricultural production DP rates for a given soil profile are determined by the crop water demand (net ET) and the irrigation method AE. Typically for alfalfa hay production in the southern California desert regions, crop water demand is assumed to be approximately 90% of net annual ET because of three to five hay cuttings per year, resulting in lower crop water demands immediately after each cutting. Irrigation water application efficiency depends in part on irrigation management and application methodology with typical values ranging from 60% to 90% for surface to sprinkler to drip irrigation techniques.

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Figure 2. Desert alfalfa hay WUE for the Antelope Valley (Palmdale station) as compared with neighbouring regions (adapted from Grismer, 2001)



Figure 3. Daily DP rates associated with the different irrigation schedules for alfalfa hay production summarized in Table I

As in the Nevada study (Stonestrom *et al.*, 2003), sprinkler irrigation methods are typically deployed in the Antelope Valley with system-wide AEs fo 80%–90%. Here, DP rates were developed for three different irrigation AEs of 70%, 80% and 90% and two annual net ET values of 90% and 100%. To bracket the broadest range of possible irrigation management scenarios, we included a winter preirrigation scenario in the analyses as sometimes in desert hay production this small midwinter preirrigation or leaching irrigation is applied to restore stand vigor and possibly leach accumulated root zone salinity. Thus, for the maximum water demand case of 100% net ET, one small (58 mm) January leaching irrigation was presumed in

T3 determining the daily DP rates (see Table III). Note that annually, the applied water depths range from 1.7 to 2.4 m for alfalfa hay production (by way of comparison, Stonestrom *et al.*, 2003, assumed 2.0–2.7 m/year in Nevada), resulting in annual DP depths of 193 to 757 mm/year, respectively. With current irrigation management, DP rates from alfalfa hay production in the American Southwest and other sprinkler irrigated arid regions of the world are expected to be towards the smaller end of this range (i.e. 150–250 mm/year). At the daily time scale, the actual irrigation event DP depth varies little from one irrigation to the next for (at the same AE values),



Figure 4. Averaged and exponentially decreasing daily DP rates for the 90% ET/70% AE alfalfa hay irrigation schedule. (Note that annual DP is the same, although maximum daily DP rates are much greater in the instantaneous recharge DP case)

although average DP rates progressively increase and peak midsummer steadily declining into the winter months.

For the vegetable (e.g. carrot and potato) crop rotations, DP rates are somewhat more variable and smaller as compared with that for alfalfa hay production. Initial planting irrigations result in individual recharge events that are much greater than the DP rate averages during the remainder of the growing season. In addition, one complete rotation cycle of approximately 14 months duration rather than 12 is considered although lag times are later computed with respect to the 1-year period for comparison purposes. AEs for the vegetable crop rotations are fairly high, roughly 85% for the entire rotation and 81%–84% for the carrot or potato crops individually. Table III summarizes the annual irrigation, AEs and resulting DP values considered in the vadose zone modelling.

#### VADOSE ZONE SEEPAGE PROCESSES AND LAG TIMES TO DEPTH

To illustrate the key processes associated with the DP recharge wetting to depths of approximately 75 m bgs, we considered accumulated alfalfa hay production DP seepage, although a progressively coarsening substrata. Next, irrigation recharge questions associated with net ET<sub>o</sub> fraction, AE and variable DP rates (i.e. Figure 4) and their effects on lag times for the simplest, most conservative sand-only case are considered. This is followed by a discussion of the lag times associated with substrata profiles that are representative of the valley. Six different subsurface porous media textures that more or less comprise the range of shallow aquifer conditions found in the valley based on the driller-log information reviewed are considered in the vadose zone modelling for seepage from alfalfa hay production. Two different subsurface textural profiles were used for the vegetable crop rotations: a uniform sand and a composite profile developed from the driller logs for a particular (Kotchian Ranch) area. First, the seepage and the associated lag times for alfalfa hay production are considered followed by those for the vegetable crop rotations. Second, model

		modeling			
Crop water use	Irrigation AE (%)	Irrigation depth (mm)	Annual SWB AE (%)	Annual AW (mm)	Annual DI (mm)
100% net ET + preirrigation	70	152	69.0	2438	757
90% net ET, no preirrigation	70	152	71.0	2134	620
90% net ET, no preirrigation	80	137	78.9	1920	406
90% net ET, no preirrigation	90	122	88.7	1707	193
100% net ET + planting – irrigation	84	8-61	Carrots <sup>a</sup>	1054 <sup>a</sup>	$170^{\mathrm{a}}$
100% net ET + planting - irrigation	81	8-61	Potatoes <sup>a</sup>	1123 <sup>a</sup>	211 <sup>a</sup>

Table III. Summary of average annual alfalfa hay and vegetable crop rotation irrigation scheduling information used in vadose zone modelling

<sup>a</sup> AW, applied water. Values for growing season only (140 days) after planting on 1 March.

parameter sensitivity is considered so as to envelope the likely range of DP lag times to a depth of 68.6 m bgs that might be expected in the valley.

One advantage of the daily calculation approach taken here is that it enables the determination of the cumulative groundwater recharge wetting 'hydrograph' resulting from F5 the annual irrigation schedule. Figure 5 illustrates the irrigation (90% net ET/70% AE) recharge cumulative seepage through a midrange textured aquifer material (loamy soils) that progressively coarsens with depth in 12.2 m increments ( $S_v$  increases from 10% to 14% and  $\lambda$ from 2.0 to 2.4). Note in Figure 5 (and those following) that the root zone DP cumulative 'hydrograph' is marked as the '1.5 m depth (or bgs)' and is shown for comparison purposes. The greater average daily DP rates occurring midsummer, or more than 100 days after the first irrigation, and the earlier starting but slower DP waters combine with later faster DP waters, resulting in greater accumulations relatively earlier than that suggested by the root zone cumulative DP alone. As a result, the recharge 'centre of mass' (310 mm cumulative DP) travels much faster than the entire mass because of the 'tailing' of very slow moving waters. This tailing is accentuated with increasing depth. The staggered or 'stepping' of the cumulative recharge results in part from the steplike structure of the DP rate F6 hydrograph as illustrated in Figure 3. Figure 6 shows the lag times between surface application and appearance at depth of the DP centre of mass and the total DP mass as taken from the data used in Figure 5. Lag times for the centre and total DP masses to reach more than 61 m deep



Figure 5. Cumulative recharge from alfalfa hay production as a function of depth and time for midrange aquifer characteristics (90% net ET/70% AE)



Figure 6. Lag times for midrange aquifer characteristics (90% net ET/70% AE)

are 1.7 and 6 years, respectively. The long tailing of the cumulative seepage at long times suggests that the centre of DP mass timing is probably a better indicator of when the wetting front reaches or passes a particular depth of interest as compared with the time for the total DP mass to reach depth. Nonetheless, plotting the cumulative DP mass with time enables determination for any fraction of the DP mass considered relevant to assess the particular lag time of interest.

# ALFALFA HAY DP RECHARGE LAG TIMES TO DEPTH FOR VALLEY SUBSURFACE CONDITIONS

On the basis of the driller-log information reviewed, typical unsaturated aquifer layers that are considered to represent the range of subsurface conditions across the valley and that for the Kotchian Ranch area were assembled and these profile characteristics are summarized in Table IV. With the exception of the alternating T4 layer and coarsening loam profiles having depths of 74.7 m, all depths modelled were 68.6 m bgs. Finally, Table V summarizes the DP recharge centre and total T5 mass lag times in years for all the different combinations of irrigation and substrata cases considered.

First, the effect of exponentially decreasing DP rates immediately after alfalfa hay irrigation events is considered to estimate the impact of the 'pulsed' recharge as

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Crop	Profile	Aquifer materials and layer thickness	$S_{y}$ (%)	λ
Alfalfa	Sand only	1.5 m soil/67 m sand	20 (sand)	3.0
Alfalfa	Clay/sand	1.5 m soil/36.6 m clay/30.5 m sand	3 (clay), 20 (sand)	1.1 (clay), 3.0 (sand)
Alfalfa	Sand/clay	1.5 m soil/36.6 m sand/30.5 m clay	20 (sand), 3 (clay)	3.0 (sand), 1.1 (clay)
Alfalfa	Sand/clay/gravelly sand	1.5 m soil/6.1 m sand/30.5 m	20 (sand), 3 (clay),	3.0 (sand), 1.1 (clay),
		clay/30.5 m coarse sand/gravel	25 (gr. sand)	3.0 (gr. sand)
Alfalfa	Alternating	1.5 m soil/24.4 m loam/6.1 m	10 (loam), 3 (clay),	2.0 (loam), 1.1 (clay),
	loam/clay/sand/clay/sand	clay/6.1 m sand/12.2 m clay/24.4 m sand	25 (sand)	3.0 (sand)
Alfalfa	Progressively	1.5 m soil/12.2 m loam coarsening by	10-14 (loam)	2.0-2.4 (loam)
	coarsening loams	12.2 m intervals to sandy loam		
Rotation	Sand only	0.61 m soil/68 m sand	20 (sand)	3.0 (sand)
Rotation	Soil/clay loam/sand	6.1 m soil/24.4 m clay loam/38.1 m sand	15 (soil), 3 (clay),	2.0 (soil), 1.2 (clay),
	-		20 (sand)	3.0 (sand)

Table IV. Representative subsurface texture and hydraulic property profiles for the Antelope Valley used in vadose zone seepage modelling for lag time determinations

Table V. Agricultural DP lag times to groundwater at 68.6 m bgs for the range of alfalfa hay and vegetable crop rotation irrigation and substrata conditions expected to occur in the Antelope Valley

				Lag time for	DP masses (year)
Crop	Description	Net ET%/AE%	$S_y/\lambda$ values	Centroid	Total
Alfalfa	Loam/clay/sand/clay/sand	100/70	10/2.0, 3/1.1 and 25/3.0	1.21 <sup>a</sup>	3.45 <sup>a</sup>
Alfalfa	Coarsening sandy loam to fine sand	100 + preirrigation/70	See Table IV	$0.80^{\mathrm{a}}$	$2.10^{a}$
Alfalfa	Coarsening sandy loam to fine sand	90/70	See Table IV	$1.52^{a}$	5.95 <sup>a</sup>
Alfalfa	Sand/tight clay/sand	100/70	25/3.0, 3/1.1 and 25/3.0	0.94	2.76
Alfalfa	Sand/tight clay/sand	90/70	25/3.0, 3/1.1 and 25/3.0	1.05	3.67
Alfalfa	Tight clay/sand	90/70	3/1.1 and 20/3.0	1.28	3.64
Alfalfa	Sand/tight clay	90/70	20/3.0 and 3/1.1	1.55	3.84
Alfalfa	Sand only	100/70	20/3.0	1.81	3.71
Alfalfa	Sand only	90/70	20/3.0	2.06	4.80
Alfalfa	Sand only	90/80	20/3.0	2.87	6.40
Alfalfa	Sand only	90/90	20/3.0	5.04	10.9
Alfalfa	Coarse sand only	90/70	25/3.0	1.91	4.50
Alfalfa	Sand only	100/70	20/3.0	1.79	3.71
Alfalfa	Sand only	90/70	20/3.0	2.06	4.80
Alfalfa	Fine sand only	90/70	17/2.5	2.24	5.24
Alfalfa	Sandy loam only	90/70	15/2.0	2.43	5.72
Alfalfa	Loam soil only	90/70	12/1.5	2.57	6.14
Alfalfa	Clay loam soil only	90/70	10/1.1	2.68	6.58
Alfalfa	Clay loam soil only	90/70	8/1.1	2.33	5.75
Alfalfa	Clay soil only	90/70	5/1.1	1.59	4.10
Alfalfa	Tight clay only	90/70	3/1.1	1.03	2.68
Alfalfa	Sand only—pulsed DP	90/70	20/3.0	0.58	7.79 <sup>a</sup>
Carrot <sup>e</sup>	Sand only	100/84	20/3.0	3.09	7.53 <sup>b</sup>
Carrot <sup>c</sup>	Loam soil/clay loam/sand	100/84	15/2.0, 10/1.2 and 20/3.0	3.12	8.19
Potato <sup>c</sup>	Sand only	100/81	20/3.0	2.74	7.12 <sup>b</sup>
Potato <sup>c</sup>	Loam soil/clay loam/sand	100/81	15/2.0, 10/1.2 and 20/3.0	2.39	7.48 <sup>b</sup>

<sup>a</sup> Lag time to depth of 74.7 m.

<sup>b</sup> 99% of total mass.

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<sup>c</sup> Crop rotations of carrots or potatoes followed by green chop and winter grains.

compared with 'stepped' average recharge on possible lag times to 68.6 m bgs. Figure 7 illustrates the cumulative DP curves for the simplest subsurface case of a sand-only porous media under conditions of averaged and variable daily DP associated with 90% ET/70% AE irrigation conditions for alfalfa hay production. The initially much greater DP rates (see Figure 4) from the pulsed as compared with the average recharge rates enable DP to reach depths of 68.6 m bgs much more rapidly; however, the exponentially decreasing much slower DP rates that follow the initial pulse increase the cumulative DP mass tailing. Because of both effects, the pulsed recharge DP centre of mass reaches 68.6 m bgs nearly 1.5 years earlier than predicted for the average DP rate, but the time



Figure 7. Cumulative alfalfa hay recharge as a function of time for a sandonly subsurface profile subjected to pulsed (instantaneous) and averaged DP rates from alfalfa hay irrigation

required for 99% of the pulsed DP recharge to reach this depth is 3 years greater than that for the average DP rate. In both cases, however, 98.5% of the DP recharge reaches the 68.6-m depth in 4.75 years after irrigation application. As the average DP recharge rates are more consistent with the quasi-steady flow modelling assumption and they result in more conservatively (greater) estimated lag times, the remaining analyses employ the average DP rates as shown in Figure 3 only depending on the crop.

The second issue related to irrigation DP recharge is the effects of net ET fraction and AE on DP lag times to depth. Examining the net ET fraction question first and again using a second or by subsystem and the Eight Science 2 illustrates

**F8** using a sand-only subsurface profile, Figure 8 illustrates cumulative DP as functions of time for the combinations of 100% net ET/70% AE and 90% net ET/70% AE. Not surprisingly, the greater overall DP and DP rates from the 100% net ET condition result in smaller lag times overall with the centroid and total DP masses for the 100% net ET case arriving at 68.6 m bgs in approximately 3 and 13 months, respectively, before those for the 90% net ET case. Coincidentally, both net ET conditions result in the same initial time to the 68.6-m bgs depth because of similar maximum DP rates from the root zone. Including the preirrigation in 100% ET/70% AE case has the effect of substantially reducing the estimated lag time to depth of the



Figure 8. Cumulative alfalfa hay DP recharge as it depends on net ET fraction at 70% AE for a sand-only aquifer profile.

DP centroid by nearly 9 months because of the early season, low ET period recharge event (see Table V). As noted earlier, however, irrigation at 100% net  $ET_o$  with a preirrigation may have been more common in decades past but is not expected to occur presently; thus, subsequent analyses largely focus on the 90% net  $ET_o$  case.

Improved irrigation AE has the effect of reducing the net root zone DP through smaller applications designed to more closely match crop water needs. Again, using the sand-only subsurface profile, Figure 9 illustrates the effect F9 of AE on cumulative DP lag times to 68.6 m bgs. Decreasing recharge rates by increasing AE from 70% to 80% and 90% not only results in smaller net annual DP but also increases centroid DP mass arrival times at 68.6 m bgs by almost 10 and 36 months, respectively. Interestingly, for an annual recharge rate similar to that of the 90% AE, Grismer et al. (2000) found that for approximately 180 mm/year of rainfall-induced recharge rate concentrated in the winter months at the coastal orchard, the wetting water content 'hydrograph' peak (or centre of mass) advanced approximately 5 m in 3 months, or if extrapolated, approximately 3.5 years to a depth of 70 m, a value between that for the 80% and 90% AE cases. However, irrigation AEs on a seasonal basis of near 90% are not likely in practice and potentially unsustainable in the longer term because of inadequate salt leaching so this analysis retains focus on 70% AE case in the discussion in the next section.

#### SENSITIVITY OF HAY DP RECHARGE LAG TIMES TO SUBSURFACE TEXTURAL PARAMETERS

As different substrata have differing soil water hydraulic properties, lag times to depth depend in part on the layering complexity of the subsurface, from sand only to sand–clay and alternating sand–clay combinations. Starting with the simplest case of a sand-only profile, Figure 10 F10 illustrates the cumulative DP or wetting front advance to depth for sand-only, clay–sand and sand-clay subsurface profiles. As noted earlier and seemingly counterintuitive, lag times for DP cumulative masses to reach depth are



Figure 9. Cumulative alfalfa hay DP recharge as it depends on AE for 90% net ET in a sand-only subsurface profile

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Figure 10. Cumulative alfalfa hay DP recharge as a function of depth and time for sand-only and clay/sand aquifer profiles (90% net ET/70% AE)

greatest for the sand-only followed by the sand-clay and then clay-sand profiles. The thickness of each layer and its relative location in the depth sequence is important towards the estimation of lag times as thicker clay layers enable greater DP rates to then enter sand layers below. F11 F12 Figures 11 and 12 illustrate this effect in part through the display of cumulative DP for the sand-clay-sand and loam-clay-sand-clay-sand profiles, respectively. Overall, relative to the sand-only profile, clay layering results in smaller DP mass lag times to depth.

Aside from the depth to groundwater chosen and the applied recharge (DP) rate,  $S_y$  (thus  $K_s$ ) and  $\lambda$  are the two key subsurface soil water parameters affecting the determination of lag times to depth from the solution of the Richards equation. From Figures 11 and 12, it seems that when considering layers of tight clay materials with very small  $S_y$ ,  $K_s$  and  $\lambda$  values (i.e.  $S_y = 3\%$ ), lag times decrease relative to the sandy profiles. However, it is also possible to have soil textures with larger  $S_y$  values but small  $\lambda$  values, typically associated with loamy materials. F13 Figure 13 shows the effects of changing  $S_y$  and  $\lambda$  values in uniform subsurface profiles on predicted lag times.

Note that as subsurface material textures coarsen towards larger  $S_y$  and  $\lambda$  values for all  $S_y > 10\%$ , DP mass lag times



Figure 11. Cumulative alfalfa hay DP recharge as a function of depth and time for sand/clay/sand aquifer profile (90% net ET/70% AE)







Figure 13. Cumulative alfalfa hay irrigation DP recharge to 68.6 m depth as it depends on subsurface hydraulic parameters (90% net ET/70% AE)

progressively increase; however, at  $S_y < 10\%$ , DP mass lag times decrease substantially. This suggests that particular combinations of  $S_y$  and  $\lambda$  values that may be associated with similarly textured materials can result in prediction of different lag times for  $S_y$  values near 10%. Nonetheless, overall DP centre of mass lag times range from 1 to 3 years for all cases considered here (see Table V). This observation suggests that of the roughly two orders of magnitude range in spatially variable estimated groundwater recharge rates as found by Cook *et al.* (1989), the subsurface soil textural conditions effect alone is likely smaller as compared with spatially variable near-surface deep drainage rates.

#### VEGETABLE ROTATION DP RECHARGE LAG TIMES T FOR SAND AND RANCH SUBSURFACE CONDITIONS

Common vegetable crop rotations across the Antelope Valley include onions, carrots and potatoes, and for comparison purposes, the approximately 14-month rotations that included carrots or potatoes, green chop and winter grains were considered in the vadose zone modelling. These crops may differ from an established

alfalfa stand as they are sprinkler or drip irrigated and have more variable shallow active root zones associated with SWB calculations. After establishing the basic processes controlling lag times in the previously mentioned analyses for alfalfa hay production, only two subsurface soil profiles are considered in the determination of lag times from vegetable crop rotations. Again for comparison purposes, a sand-only profile is used to set the upper limit of lag times likely from crop rotation DP. The second profile is a composite from three driller logs taken at the Kotchian Ranch. SWB determinations of irrigation schedules were similar to those used at the Kotchian Ranch in the past decade. In these schedules, the starting date is 1 March rather than 1 January as with the alfalfa hay production and that the bulk of the overall recharge is associated with vegetable production in the first 140 days after 1 March. After the vegetable production, there is a short fallow period of no DP recharge then light irrigations associated with the green crop, a second short fallow period and then the initial irrigations to establish the winter wheat-barley crop. Calculated water use between the two rotations for averaged net ET conditions differed slightly from that measured at Kotchian Ranch; the calculated average water use for potatoes was slightly greater than measured whereas that for carrots was slightly less. Nonetheless, water-use records from the Ranch suggested that the irrigation schedule resulting in the calculated DP recharge rates was reasonable and likely slightly underestimate actual rates encountered in the field.

Analogous to Figure 10 for alfalfa hay production, AF14F15 Figures 14 and 15 illustrate the cumulative DP recharge lag times associated with the carrot and potato crop rotations, respectively. As noted earlier, the bulk of DP recharge occurs early with long tailing of the cumulative DP because of fallow periods and light irrigations associated with the green chop and grain crops after harvest of the carrot or potato crops. Cumulative DP recharge through the Ranch profile as compared with the sand-only profile occurs more quickly during the vegetable growing season because of the thick clay loam



Figure 14. Cumulative carrot rotation DP recharge as a function of depth and time for sand-only and Ranch composite subsurface profiles (100% net ET/84% AE)



Figure 15. Cumulative potato rotation DP recharge as a function of depth and time for sand-only and Ranch composite subsurface profiles (100% net ET/81% AE)

layer but then slows comparatively much later in the rotation. Overall, however, the effects of subsurface material layering on DP mass centroid or total mass lag times are relatively minor. On the basis of the recharge associated with a single calendar year rather than the 14-month rotation period, the lag times of DP mass centroid recharge from the vegetable crop rotations are slightly greater on average, although similar in range to those from alfalfa hay production. Total DP mass recharge lag times for the vegetable rotations are 1–3 years greater on average than those from alfalfa hay production due in part to the likely greater irrigation AEs and the shorter growing season (140 vs 365 days), resulting in significantly less root zone drainage.

#### SUMMARY AND CONCLUSIONS

Subsurface recharge through unsaturated substrata is a complicated process in concept that is controlled largely by near-surface seepage rates and also by the soil water hydraulic properties of the intervening layers between surface and groundwater. The estimation of the lag times to groundwater supplies at tens of metres depth in arid and semiarid regions associated with irrigation-induced root zone drainage or DP is critical towards the closure of basin or regional water balances directed at assessing long-term groundwater yields as well as the estimation of impacts on groundwater quality. Often, the necessary data describing the subsurface porous media hydraulic properties are unavailable and estimates are made on the basis of soil texture. Lacking the vadose-zone hydraulic properties has made the estimation of surface recharge lag times to groundwater at depth difficult, if not simply disregarded. Here, a coupled root zone SWB and simple one-dimensional vadose-zone model is developed. The root zone SWB develops the averaged daily root zone drainage or DP rates from alfalfa hay and carrot-potato crop rotation production in the Antelope Valley of California, USA, which are used in the vadose = zone model to estimate lag times to groundwater at depths of 69-75 m bgs. The vadose-zone model relies on only two

subsurface hydraulic parameters that can be estimated from driller-log information describing the subsurface profile textural variations enables this approach to be used widely where limited subsurface lithology information exists. The information summarized in Table V should be useful in this latter regard.

Lag times for differing irrigation recharge conditions associated with varying ET and crop production as well as several different substrata profile cases were determined so as to ascertain the likely range of agricultural recharge lag times that may have occurred or are occurring across the Antelope Valley and to address the research hypotheses outlined earlier. As noted in several studies, groundwater recharge in arid and semiarid regions is often episodically driven by rainfall or localized irrigation. With respect to the first hypothesis, considering irrigation events as instantaneous recharge rather than averaged across the time between irrigations resulted in recharge mass centroid reaching groundwater at 69 m approximately 3.5 times faster (0.58 vs 2.06 years for sand-only profile), but the time required for the near total recharge mass was twice as long. Although the hypothesis that there is 'little to no effect on estimated lag times' is rejected, the practical implications of assuming averaged recharge rates in regional groundwater balances are likely satisfactory given the much longer times required for total pulsed recharge to reach groundwater and the range of lag time estimates. However, this aspect may require further investigation. From Figures 10-15, it is clear that irrigation-induced DP recharge to groundwater is not singular events within the year (hypothesis 2) but rather continuous processes much like streamflow hydrographs as they develop within a watershed, suggesting that this hypothesis is accepted. Finally, at the very small recharge rates likely encountered in irrigated crop production in arid regions, clay layers at depth are not necessarily impediments to groundwater recharge (hypothesis 3) greatly increasing lag times. Here, subsurface profiles that included clay layers resulted in slightly smaller lag times to groundwater from the same root zone drainage rates as compared with sand-only profiles (see Table V), suggesting that this hypothesis is accepted.

In summary, lag times to 69-75 m bgs for DP mass centroids from irrigated agriculture in the Antelope Valley roughly ranged from 1 to 3 years, whereas significant tailing of slow percolating waters increases the total DP mass lag times for up to approximately 8 years after surface application in all but the 90% AE alfalfa hay production case through coarse sand. For the layered substrata conditions more likely to occur across the valley, total DP mass lag times to 68.6 m bgs are 3-4 years after surface application for alfalfa hay production and roughly 7 years for vegetable crop rotations. The greater total DP mass lag times associated with the vegetable crops is due to the shorter growing season and net smaller DP rates and masses as compared with that for continuous alfalfa hay production. The comparison of DP centre of mass lag times is likely more appropriate in terms of estimating groundwater recharge timing impacts from agriculture.

The presence of clay layers in the subsurface profile tends to decrease DP lag times to depth as compared with sandonly profiles.

Overall, the coupled model flow calculation results suggest that near-surface recharge from the irrigation of established alfalfa hay stands or vegetable crop rotations to unconfined aquifers at depths of tens of metres in semiarid regions is on the order of 150-250 mm/year with current irrigation technology and management. Furthermore, this recharge is time dependent within the year and should not be considered as a single instance of recharge to the aquifer. Improved irrigation AEs reduce DP recharge rates and significantly increase lag times to groundwater. DP recharge hydrograph peaks or centres of mass most likely have reached groundwater at depths of approximately 70 m in less than 3-4 years in the Antelope Valley, particularly in decades past when AEs were likely much smaller than those currently. Finally, DP recharge lag times are more controlled by irrigation or water application timing and rates rather than subsurface soil water hydraulic properties or spatial heterogeneities in these properties. That is, near-surface spatially variable recharge rates from locations where water accumulates such as topographic depressions, stream channels or wadis and irrigated areas are likely orders of magnitude greater than that in the adjacent dryland plains.

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