Technical Report: Modeling Nitrate Leaching Risk from Specialty Crop Fields During On-Farm Managed Floodwater Recharge in the Kings Groundwater Basin and the Potential for its Management

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By

P.A.M. Bachand[1], S.M. Bachand[1], H. Waterhouse[3], J. Rath[2], M. Ung[2], S. Roy[2] , V. Kretsinger[4], B. Dalgish[4], W. Horwath[3], H. Dahlke[3], C. Creamer[5], J. Choperena[6] , and D. Mountjoy[6]

[1]Bachand & Associates, Davis, CA
[2]Tetra Tech, Lafayette, CA
[3]Land, Air and Water Resource, University of California Davis
[4]Luhdorff & Scalmanini, Consulting Engineers (LSCE), Woodland, CA
[5]Kings River Conservation District, Fresno
[6]Sustainable Conservation, San Francisco, CA

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Contents

Figures

Tables

Executive Summary

This project has focused on better understanding the potential impact of On-Farm Flood Capture and Recharge (OFFCR) on groundwater quality pertaining to salts and nitrate and on assessing potential management opportunities. To achieve these goals, we used a combination of field and modeling studies. For the field study, soil cores were taken to a depth of 30 feet in replicate across fields with three different specialty crops identified as important to the San Joaquin Valley (tomatoes, almonds, vineyards) and with potential suitability for OFFCR. A prime goal of the field study was to provide data for parameterizing two models developed to assess nitrate, salt and water transport through the vadose zone, prior to percolating into the groundwater aquifer. However, the field study also resulted in key findings that show its value as a stand-alone study:

- Nitrate concentrations are highest in the upper vadose zone and affected by texture. Those effects are not evident in the deeper vadose zone.
- Vadose zone nitrate concentrations are affected by the crop grown. These results suggest an opportunity for lower legacy mass transport for grapes and higher legacy mass transport for both tomatoes and almonds.
- Variability in individual farmers' past and present fertilizer and water management practices contributes to different legacy salt and nitrate loads in the vadose zone.

Data from the field study and other related and concurrent OFFCR field efforts were used during model development. The overall modeling approach was designed to model nitrate and salt transport for lands under OFFCR operation for different crop types, vadose zone characteristics and groundwater characteristics. The defined goals of this design and modeling approach were to: 1) model nitrate and salt movement through the vadose zone and into groundwater; 2) test the model against scenarios that consider different recharge rates, cultural practices, soil types, and depths to groundwater, assessing the timing and magnitude of loading through the vadose zone and the effects on underlying groundwater; and 3) recommend management practices to mitigate potential groundwater impacts. To achieve these goals, two models were integrated to simulate nitrate and salt transport through the vadose zone to groundwater under different scenarios: a 1D Hydrus model and an analytical groundwater model (AGM).

Several significant methodological advances have occurred from this study as related to the integrated models. First, significant effort and resources were put into the development of the Hydrus model. For the Hydrus model, an important outcome of this effort was the documentation of a method to define typical inputs (e.g., nitrogen, irrigation, recharge) and then to put numbers to those inputs. These inputs were used to develop a Hydrus model that reasonably models nitrate and salt transport through the vadose zone, based upon a comparison to our field data and to results from other OFFCR studies. Second, an AGM was developed that allows testing of various OFFCR scenarios for different representative groundwater basins. This AGM, integrated with Hydrus, provides an important tool to widely assess OFFCR across the Central Valley and across areas interested in implementing OFFCR. This work provides an analytical tool to test OFFCR, anticipate potential outcomes to groundwater, and enable the planning and testing of mitigation measures.

For this project, a number of scenarios were identified to test the potential impacts of OFFCR to groundwater and the sensitivity of those impacts to changes in crops, cultural practices, groundwater pumping, etc. Early results from the models suggest a number of groundwater

quality effects. Simulated groundwater quality effects are most noticeable near the OFFCR area at the first encountered groundwater depths. The magnitude of the groundwater quality effects decreases spatially with distance from the OFFCR area and with depth within the groundwater and temporally until they are effectively negligible. Increased quantities of recharge water applied during OFFCR events may not greatly affect groundwater quality. Rather, early results suggest the magnitude of legacy constituents flushed from the vadose zone as well as the magnitude of salts and nitrogen contributed by ongoing fertilization cultural practices are major determinants. Improved agronomic water and nutrient management practices in the future reduce longterm nitrogen loading effects. Over time, longterm legacy loading effects diminish as the vadose zone is flushed with additional clean recharge water. Further work is needed to further test fertilizer and crop management and groundwater sensitivity to these practices, and to assess the opportunities and constraints of regionally expanding OFFCR. Work is ongoing in part funded through leveraging funds from the National Institute of Food and Agriculture, Bachand & Associates, and Tetra Tech. Completion of these runs will provide important information and insight into OFFCR and groundwater quality management.

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Technical Project Report

This Specialty Crop Block Grant project assessed the potential impact of On-Farm Flood Capture and Recharge (OFFCR) on groundwater quality related to the flushing of salt and nitrates from agricultural lands. Technical work conducted included development of the experimental design, collection of field and existing data sources for model calibration and validation, and development of an integrated model to assess nitrate, salt and water transport through the vadose zone and into the groundwater aquifer. This report provides a summary of these technical efforts, findings, and recommendations for next steps to further validate and apply the models to other potential locations in California's Central Valley where groundwater replenishment is a high priority.

I. Experimental Design

An experimental design was laid out for the project, integrating field data collection and modeling. The overall approach is detailed below.

Modeling Approach

The overall modeling approach was to be able to model transport of nitrate and salts for lands that would be used for OFFCR for different crop types, vadose zone characteristics and groundwater characteristics. The defined goals of this design and modeling approach were to: 1) model nitrate and salt movement through the vadose zone and into groundwater; 2) test the model against scenarios that consider different recharge rates, cultural practices, soil types, and depths to groundwater, assessing the timing and magnitude of loading through the vadose zone and the effects on underlying groundwater at various depths, distances, and times; and 3) recommend management practices to mitigate potential groundwater impacts.

To achieve these goals, two models were developed to simulate nitrate and salt transport through the vadose zone to groundwater under different scenarios: a 1D Hydrus model and an analytical groundwater model (AGM) (Figure 1). Using that modeling structure, an approach was designed to test groundwater quality effects from OFFCR considering the effects of crops grown, recharge intensity used, the recharge area size, nitrogen management practices, soil stratigraphy, depth to groundwater, groundwater pumping (simulated through groundwater velocity), and ambient groundwater concentrations. For the 1D Hydrus model that describes the vadose zone, inputs were used to characterize farm practices (e.g., nitrogen fertilization, irrigation); OFFCR methods (e.g., recharge area size, recharge intensity, frequency, period), and soil textures in the root zone and in the deeper vadose zone. Nitrogen and hydrologic inputs were defined by crop type based upon UC Davis, UC Cooperative Extension and other published sources.

Outputs from the vadose zone model were then input into the AGM. As each model was separate, different Hydrus runs could be fed into different groundwater model runs. Together, these models were used to describe nitrogen, salts and hydrologic transport from specific crops through the vadose zone and into groundwater for the different modeled scenarios developed to understand OFFCR effects and to be able to develop management and land use recommendations.

Define Modeling Scenarios

Table 1 presents the modeling scenarios identified for testing under this project. Scenarios were first identified early in the project to assess the different factors that affect vadose and groundwater. The main factors for testing in the scenarios were the effects of crop fertilizer and irrigation management, the effects from vadose zone texture, and the effects from different recharge strategies. The scenarios presented here represent the most recent iteration. The integrated model design plan focused on testing how different independent variables affect constituent and flow transport through the vadose zone: e.g., vadose zone core texture, irrigation levels, recharge intensity, size of recharge area, depth to groundwater, crops and their nutrient management, ambient groundwater quality, groundwater pumping characteristics (as defined by groundwater velocity). These different scenarios are tested against a "Reference" scenario, defined in the table as Grapes under specific management and in certain environments. The table defines representative conditions as have been identified by the team and are covered in more detail in a project technical memorandum which will be finalized as individual publications[1].

Modeling Sites

The modeling area has been generally defined as the Tulare Lake Hydrologic Region. Much effort on recharge has been ongoing throughout the region including the first field tests[2], implementation and testing of the first full-scale system[3] and considerations for regional scale-up[4]. Modeling sites defined as representative to groundwater and vadose zone conditions are shown in Table 2.

Current Status and Achievements

The purpose of the experimental design was to provide a framework and structure for the research and to coordinate collaborative efforts. With collaboration amongst several organizations involved across the spectrum of research, consulting and planning, this task was critical in working towards that end. Moreover, this project tackles a complex problem by: 1) developing a better understanding of the vadose zone and its implications on water and constituent transport; and 2) leveraging different modeling tools to understand how to best implement OFFCR.

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[1] Bachand, P.A.M., S.M. Bachand, H. Waterhouse, J. Rath, M. Ung, V. Kretsinger, B. Dalgish, W. Horwath, H. Dahlke, C. Creamer, J. Choperena and S. Roy. 2017. Technical Memorandum: Modeling Nitrate Leaching Risk from Specialty Crop Fields During On-Farm Managed Floodwater Recharge in the Kings Groundwater Basin and the Potential for its Management. Technical Memorandum is currently under preparation as funded through this and other grant projects and chapters will be submitted as individual peer reviewed manuscripts. Submission planned for 2017.

[2] Bachand PAM, Trabant S, Vose S, Mussetter B. 2013. McMullin On-Farm Flood Capture and Recharge Project: Hydraulic and Hydrologic Analyses (H & H). Final report, TO# 01, prepared for Kings River Conservation District for submittal to California DWR.

[3] KRCD. 2012. McMullin On-Farm Flood Capture and Recharge Project, Summary Project. FloodSafe California Project, California Department of Water Resources awarded to Kings River Conservation District: BMS No:2010FPCP0014. Awarded July 2012.
http://www.water.ca.gov/floodmgmt/fpo/sgb/fpcp/docs/Summary_McMullin.pdf

[4] Bachand, PAM, S.B. Roy, N.R. Stern, J.Choperena, D. Cameron and W.R. Horwath. 2016. On-Farm Flood Flow Capture – Addressing Flood Risks And Groundwater Overdraft In The Kings Basin With Potential Applications Throughout The Central Valley. Calif Agr. 70(4): 200-207.

The process of developing the experimental design helped focus the efforts and expertise of the different team members to develop a relevant and functioning modeling approach in the context of today's water and specialty crop environment.

Table 1. Scenario Testing Design Plan

Table 1 presents the scenarios planned to be simulated using the Hydrus and AGM models. The blue font represents the reference recharge scenario (Reference) against which all effects are tested under the different scenarios.

Independent Variables [1]					Scenario and Its Definition								
						1	2	3	4	5	6	7	8
	Name	Value		Units	Control [1]	Effects of BMP for Nutrient Mgmt Plan on different crops	Effects of Soil Texture	Depths of Vadose Zone	Effects of different crops on GW (included in Scenaro 1)	Effects of different recharge scale on GW	Effects of Recharge Strategy	GW velocity	Ambient GW
Crop and Nutrient													
	Spec Crop 1	Tomatoes	BP Farm (414)	lbs-N/Ac		x							
	Spec Crop 2	Almonds	BP Farm (428)	lbs-N/Ac		x							
	Spec Crop 3	Grapes	BP Farm (74)	lbs-N/Ac	x	x	x	x		x	x	x	x
	Spec Crop 1	Tomatoes	Low Input(276)	lbs-N/Ac		x							
	Spec Crop 2	Almonds	Low Input(204)	lbs-N/Ac		x							
	Spec Crop 3	Grapes(22)	Low Input	lbs-N/Ac		x							
Irrigation													
	BAU [4]	1.1 X BP		in/y									
	BP Farm [4]	1.05 X ETc		in/y	x	x	x	x		x	x	x	x
Recharge [2]													
	Rotating	15: 0.58; 150: 0.48; 500: 0.41		in/d							x		
	Dedicated	15: 2.3; 150: 1.92; 500: 1.65		in/d	x	x	x	x		x	x	x	x
Size (cfs)													
	Field	15		acres						x			
	Farm	150		acres	x	x	x	x		x	x	x	x
	Farm Complex	500		acres						x			
Texture													
	Sandier	Core 1			x	x	x	x		x	x	x	x
	Clayier	Core 2					x						
Depth to GW													
	low	100		ft				x					
	Middle	150		ft	x	x	x	x		x	x	x	x
	High	200		ft				x					
Velocity													
	Low	H: 0.2, V: 0.002		ft/d	x	x	NA	NA		x	x	x	x
	High	H: 0.8; V:0.008		ft/d								x	
GW Water Quality [3]													
	Upper Quartile	NO3-N: 10; TDS: 700		mg/L									x
	median	NO3-N: 5; TDS: 400		mg/L	x	x	NA	x		x	x	x	x
	Lower Quartile	NO3-N: 2.5; TDS: 250		mg/L									x
Total Scenarios													
	All	17			1	6	2	3		3	2		
	Minus Control	12			1	5	1	2		2	1		
Modeling Tools													
	Hydrus	13			x	x	x	x		x	x	x	x
	GW	13			x	x	x	x		x	x	x	x

Notes

1 Control shaded blue in Independent Variables

2 Rotating is simulated using 1/4 of infiltration rate under dedicated recharge (2.4 in/d). Dependent upon system capacity

3 BAU is used for 25-y runup to achieve equilibrium conditions in vadose zone

4 Irrigation under Best Practices is estimated at 1.05 X ETc (Crop ET). BAU is estimated at 10% higher than BP

Table 2. Groundwater and vadose zone conditions selected for modeling sites representative of the Tulare Hydrologic Region and the Kings Basin

Vadose Zone Thickness						
	Location					**Source**
Depth to Groundwater (ft below GSE [4])	**Fresno, SR99 & SR180**	**Raisin City**	**NE Helm at SR145**			
Spring 2015	90	160	260			CASGEM, 2017
Spring 2017	90	160	200			CASGEM, 2017
Average	90	160	230			
Modeled	*100*	*150*	*200*			
Groundwater Zones and Model Sample Depths						
Available Data (ft below water table)	**Value**					
Domestic Well Depth within Saturated Aquifer	75					CVSalts [1]
Saturated Production Zone	324					CVSalts [1]
Selected Model Sampling Depths (ft below water table)						
Upper Zone	*10*					
	40					
	70					
Lower Zone	*130*					
	190					
Water Quality Ranges	**Lower Q**	**Median**	**Upper Q**	**Mean**	**Reg. 2, 3**	
TDS (mg/L)						
Upper Zone	295	408	662	544		CVSalts [1]
Lower Zone	211	295	495	395		CVSalts [1]
Regulatory Standard					500	CCR Title 22. Div. 4, R-21-03, May 2006[2]
Selected Model Ambient Levels	*250*	*400*	*700*			
NO3-N (mg-N/L)						
Upper Zone	3.6	5.9	9	7.2		CVSalts [1]
Lower Zone	2.3	4.6	8.8	6.6		CVSalts [1]
Regulatory Standard					10	Fed & CA MSCls, July 2014 update [3]
Selected Model Ambient Levels	*2.5*	*5*	*10*			
Groundwater Velocity (ft/d)	Low	High				
Observed Range and Ambient Modeling Levels						
Horizontal	0.16	0.81				
Vertical	0.002	0.009				

Notes
1 CVSalts High Resolution Geodatabases
2 EPA National Secondary Drinking Water Regulation
3 EPA and CA drinking water standard
4 GSE = Groundsurface Elevation

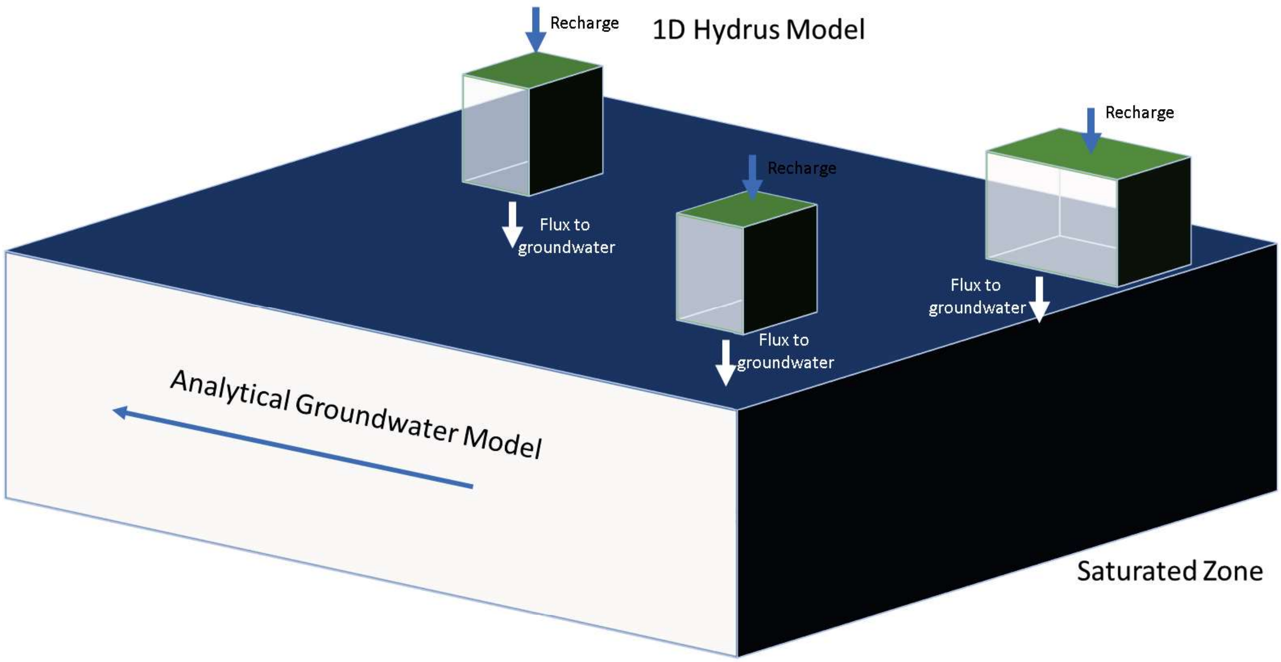


Figure 1. Modeling Framework

This project uses a 1D Hydrus model as an input to an analytical groundwater model (AGM). The 1D Hydrus model is used to test OFFCR efforts for different crops, soil stratigraphy, and cultural practices (e.g. irrigation, fertilization). Outputs from the Hydrus model enable the groundwater model to predict groundwater chemistry responses to OFFCR inputs temporally and spatially. These results will enable testing of different land uses and management practices as a way to best protect groundwater quality under OFFCR.

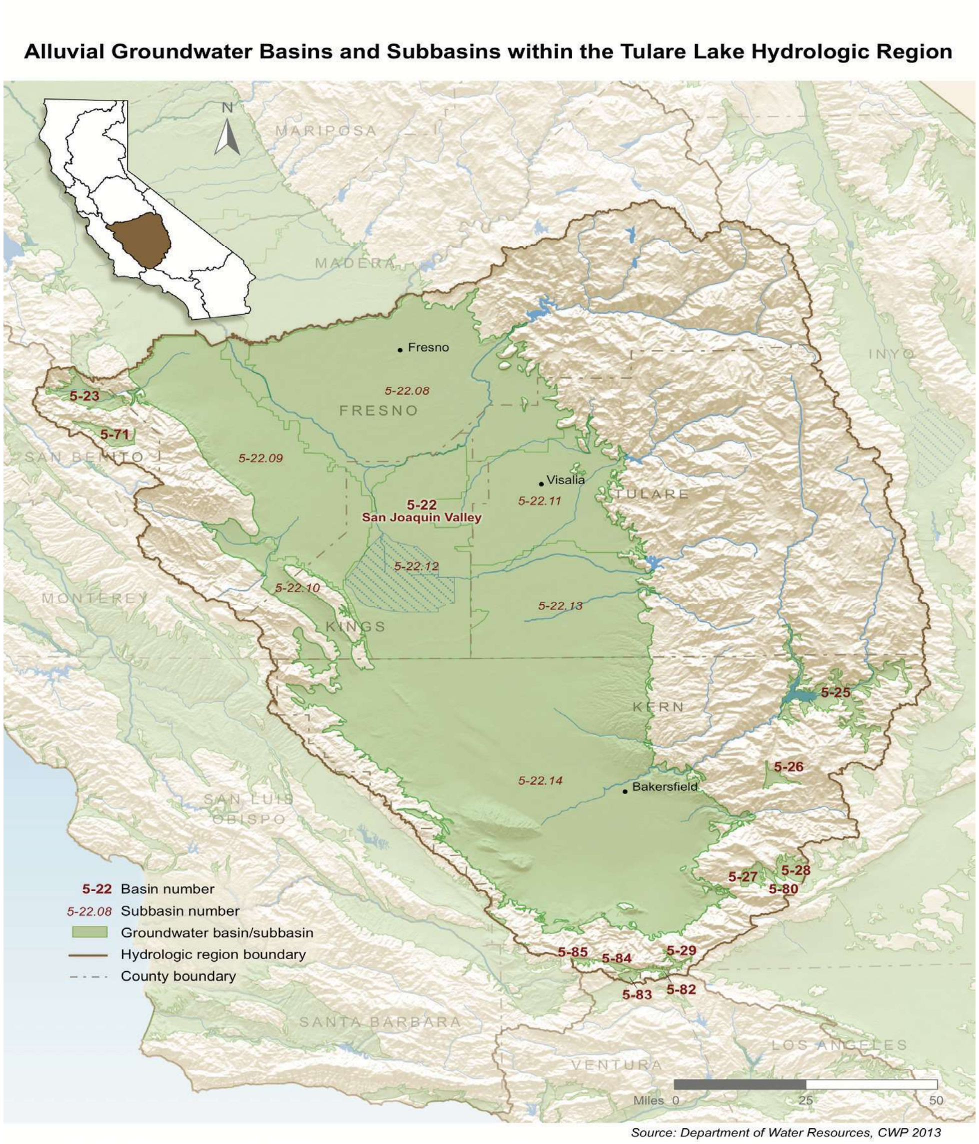


Figure 2. Study Area.

The site for modeling is the Tulare Lake Hydrologic Region. Groundwater and vadose zone conditions were based upon conditions typical for this region. Field data were collected from within the Study Area.

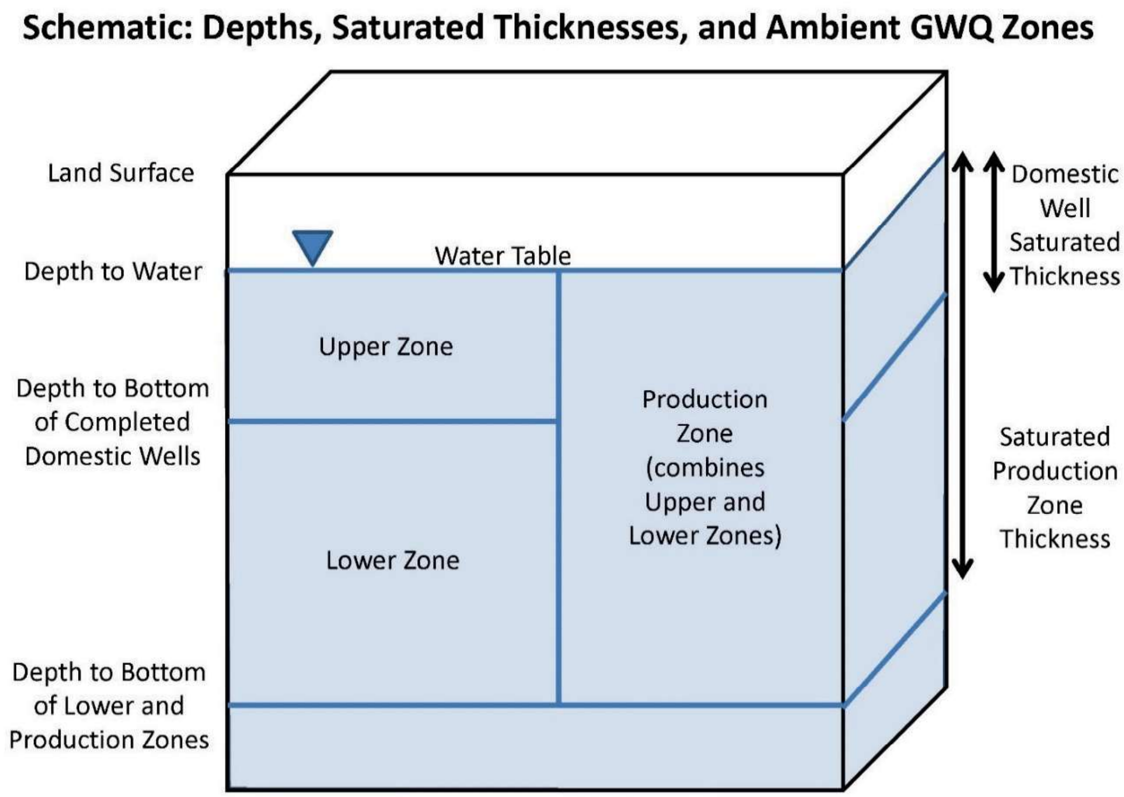


Figure 3. Groundwater schematic

This schematic describes upper and lower zones in the groundwater system typical for the Study Area and defines the production zone from which groundwater is pumped. The production zone is the main zone of interest when considering the quality of groundwater.

II. Data Collection for Model Calibration/Validation

This task was primarily focused on model calibration. A variety of data sources were targeted under this project to be used for model calibration, and these are discussed below. Additionally, this effort expanded into other areas. Particularly, this project was able to leverage other data sources for model validation and also to provide a stand-alone analysis of the vadose zone as related to crop types. These additional efforts are also discussed below.

Targeted data sources

1. **Hydrogeologic, Hydrologic and Soil Series Data.** A variety of soil sources were assessed; e.g. United States Geological Survey Central Valley Hydrologic Model (CVHM), Natural Resource Conservation Service (NRCS) soil survey data, UC Davis Soil Agricultural Groundwater Banking Index (SAGBI) data, and Caltrans borelogs. These data provided an overview of the hydrogeologic conditions and soils for the area. Specific to this project, GeoProbe data were collected and ultimately provided the most reliable and defensible source of data for use in the Hydrus Model and the AGM.
2. **Groundwater and Surface Water Nitrate and Salinity Data.** Groundwater chemistry and hydrogeologic characterization were provided through leveraging ongoing area efforts related to CV-SALTS compliance and compliance with the Central Valley Regional Board Irrigated Lands Regulatory Program, particularly as related to groundwater protection and management.
3. **Vadose Zone Soil Moisture, Chemistry and Infiltration Rates.** These data were generated through field work utilizing GeoProbe coring at identified sites selected as representative of the Tulare Lake Hydrologic Region. This is described in greater detail below. Other data sources were utilized for parameterizing the Hydrus model. These are also described below.
4. **Root Zone Chemistry Data** were primarily from GeoProbe data and other sources as described below.
5. **Industry and Collaborator Cultural Practices:** Fertilizer and irrigation data were developed based upon interviews with participating growers, input from UC Cooperative Extension specialists, CDFA fertility and irrigation guidelines, USDA National Agricultural Statistics Service (NASS) data and a review of the published literature as related to growing tomatoes, almonds and grapes. More detail and information on those sources can be found at Bachand et al (2017).[1]

GeoProbe Vadose Zone Field Study

The original concept for this project was to leverage different data sources to provide modeling information for the Hydrus model. These other sources are described above but after much review were found inadequate for developing a working vadose zone model. Thus, the project team focused on collecting vadose zone data to depths of 30 feet on fields planted with the different crops of interest and considered to represent a steady state condition with regard to transport and accumulation of salts and nitrate in the upper vadose zone under specific farming conditions (e.g. crops, cultural practices)..

Summary of Data Collection

The study area includes six farms in the Kings River Basin west of Fresno, CA. Replicate cores (N=3) were collected to depths of 30 ft under almond, tomatoes and wine grapes for two different NCRS hydrologic soil classes, Class A and Class C/D (Table 3). Class A soils are defined as soils with low runoff potential, with saturated hydraulic conductivity greater than 5.67 inches/hour (NRCS Part 630 Hydrology National Engineering Handbook), Class C soils are defined as having moderately high runoff potential and saturated hydraulic conductivity 0.14 inches/hour to 1.42 inches/hour and Class D soils have high runoff potential with saturated conductivity less than 0.14 inches/hour. Class C and Class D soils on farmland were considered in this study as many of these soils are deep tilled to remove restrictive soil horizons and to increase infiltration rates especially in orchard and vineyard systems (O'Geen et al. 2015). Cores were analyzed in the lab for NO3 , texture, moisture and electrical conductivity. For the first three feet, subsamples were taken every foot. Below that depth, samples were taken based on morphological changes within the core where distinct layers were identified. Where a lighter textured soil overlay a heavier texture layer, a sample was taken in the middle of the sandy layer, at the top of the heavier texture layer, and in the middle of the heavier texture layer to capture any NO3 that may have accumulated at the top of the heavier texture layer . Samples were analyzed statistically to assess differences on chemistry as related to texture, crops and individual farm.

Summary of Key Data Findings

Core data provided interesting data on the chemistry as related to farm practices and soil classes:

1. **Nitrate concentrations are highest in the upper vadose zone and are affected by texture. Those effects are not evident in the deeper vadose zone.**
   Nitrate pore water concentrations decreased with depth for all crop types. For lower permeability soils, nitrate concentrations were higher near the surface than for higher permeability soils, suggesting possible mechanisms such as evapoconcentration and /or slower downward movement. These distributions resulted in statistically significant differences in NO3 (ug N/g soil) between soil hydrologic classes A (5.26 ug N/g soil) and C/D (7.18 ug N/g soil) in the top 4 meters, with group C/D soils having higher NO3 levels compared to group A soils. However, this relationship disappeared below the top 4 meters with no statistical difference between soil hydrologic classes. These differences in the upper 4 meters suggest texture may affect nitrate evapoconcentration and transport (Table 4).

2. **Vadose zone nitrate concentrations are affected by the crop grown. These results suggest an opportunity for lower legacy mass transport for grapes and higher legacy mass transport for both tomatoes and almonds.**
3. Throughout the entire sampled profile, soil NO3 concentrations were significantly higher in almonds (7.07 ug N/g soil) and tomatoes (7.59 ug N/g soil) compared to grapes (4.17 ug N/g soil). This outcome held the same pattern above four meters. Below four meters soil NO3 concentrations statistically differed across all 3 cropping systems in the

following decreasing order: tomatoes (5.94 ug N/g soil)>almonds (4.82 ug N/g soil)>grapes (2.63 ug N/g soil) (
Figure 6). Similar findings were found for total NO3 load. Grapes NO3-N load (495.37 kg N/ha) was statistically lower in grape cropping systems compared to almonds (829.08 kg N/ha) and tomatoes (816.69 kg N/ha), with no statistical difference between almond and tomato cropping systems. The same relationship of total NO3 loading between cropping system was found when examining the top four meters and below four meters. The top four meters represents 61%, 62% and 55% of the total NO3 load for grapes, almonds, and tomatoes respectively. These findings suggest the type of crop grown will affect the potential mass transport of legacy vadose zone N under OFFCR.

4. **Farmers' varied management practices confound vadose zone chemistry effects of crops.**
   Vadose zone chemistry differed under different farmer management. Within almond cropping systems, Alm-A-2 had significantly higher pore water NO3 throughout the nine-meter profile compared to Alm-A-1, Alm-CD-1, and Alm-CD-2, with Alm-CD-2 having the lowest concentrations (Figure 7A). Across the nine-meter profile TDS did not statistically differ across farms. However, when examining the data within almond cropping systems, TDS did vary by farmer with Alm-CD-2 having statistically lower TDS compared to Alm-A-2 (Figure 7B). Some of these differences showed up in the other crops though definitive comparison of different crops for different farmers was not possible as all crops were not grown by all farmers. However, the data suggests that farmers' unique production objectives and past and current management choices confound the vadose zone chemistry of similar crops.

Table 3. Experimental design

A total of 36 cores were selected to a depth of 30 feet. Twelve field sites were sampled. Specific field sites were distinguished by crop type (i.e.. almonds, tomatoes, wine grapes), two soil hydrologic classes (i.e., A, C/D) and two location replicates (i.e., location 1, location 2). Three replicate cores (N=3) were sampled at each site.

Site Code	Crops	Soil Hydrologic Class	Location Replicate
Alm-A-1	Almonds	A	1
Alm-A-2	Almonds	A	2
Alm-CD-1	Almonds	C/D	1
Alm-CD-2	Almonds	C/D	2
Tom-A-1	Tomatoes	A	1
Tom-A-2	Tomatoes	A	2
Tom-CD-1	Tomatoes	C/D	1
Tom-CD-2	Tomatoes	C/D	2
WGr-A-1	Wine Grapes	A	1
WGr-A-2	Wine Grapes	A	2
WGr-CD-1	Wine Grapes	C/D	1
WGr-CD-2	Wine Grapes	C/D	2

Table 4. Pearson correlation coefficients of percent sand, percent silt, percent clay, and moisture vs pore water nitrate in the upper 4 meters.

In the upper four meters of the vadose zone, soil texture affected nitrate pore water concentrations and moisture. Moisture, total dissolved solids and texture (i.e. % sand, silt, and clay) were able to explain 39% of the variation in pore water NO3 concentrations (adjusted R^2= 0.39). Percent sand and silt and moisture had the strongest correlation with pore water nitrate. Asterisk indicates significant correlation (p<0.05).

	Pore Water Nitrate (mg/L)	**TDS (mg/L)**	**Moisture (g/g)**
% Sand	0.57*	0.09*	0.47*
% Silt	0.35*	0.19*	0.82*
% Clay	0.09*	0.06	-0.05

Figure 4. Core sample collection.

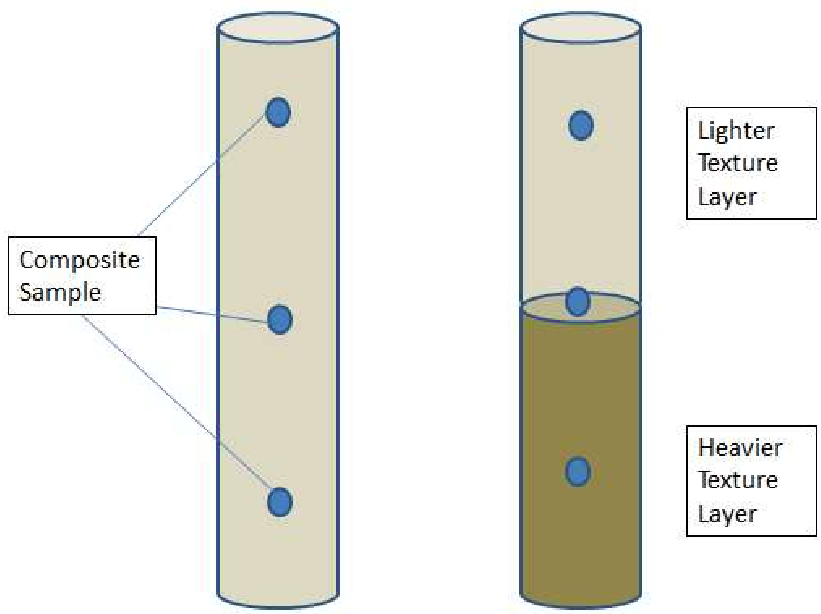


Figure 5. Pore water nitrate profiles.
Nitrate concentrations decrease with depth for all crop types. For lower permeability soils, nitrate concentrations are higher near the surface than for higher permeability soils, suggesting possible mechanism suchas evapoconcentration and /or slower downward movement.

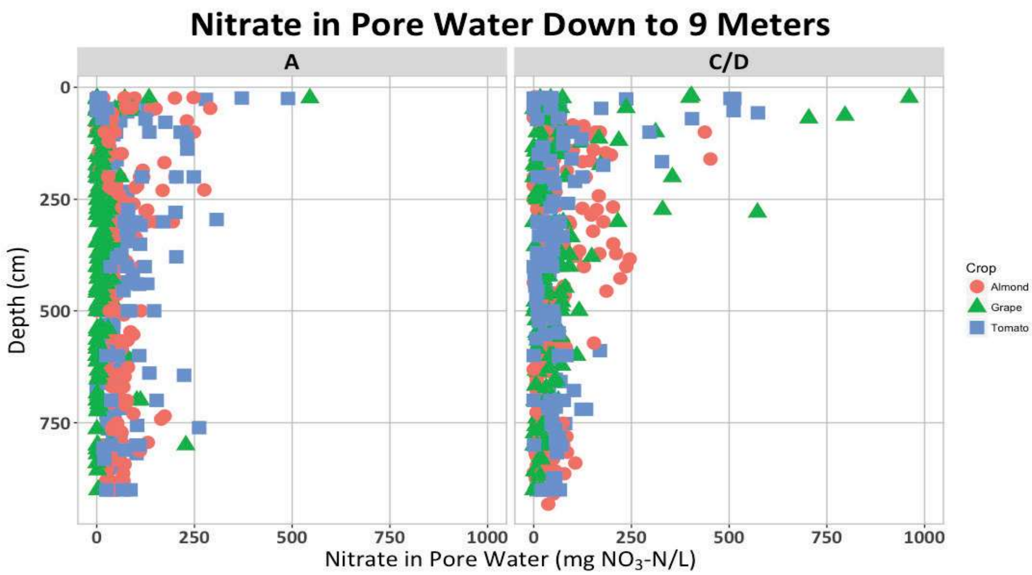


Figure 6. Mean soil NO3 (ug N/g soil) concentrations at varying depths; the entire 9 m profile, the top four meters, and below four meters.
Throughout the entire sampled profile, soil NO3 concentrations were significantly higher in almonds (7.07 ug N/g soil) and tomatoes (7.59 ug N/g soil) compared to grapes (4.17 ug N/g soil). This outcome held the same pattern above four meters. Below four meters, soil NO3 concentrations statistically differed across all three cropping systems in the following decreasing order: tomatoes (5.94 ug N/g soil)>almonds (4.82 ug N/g soil)>grapes (2.63 ug N/g soil).

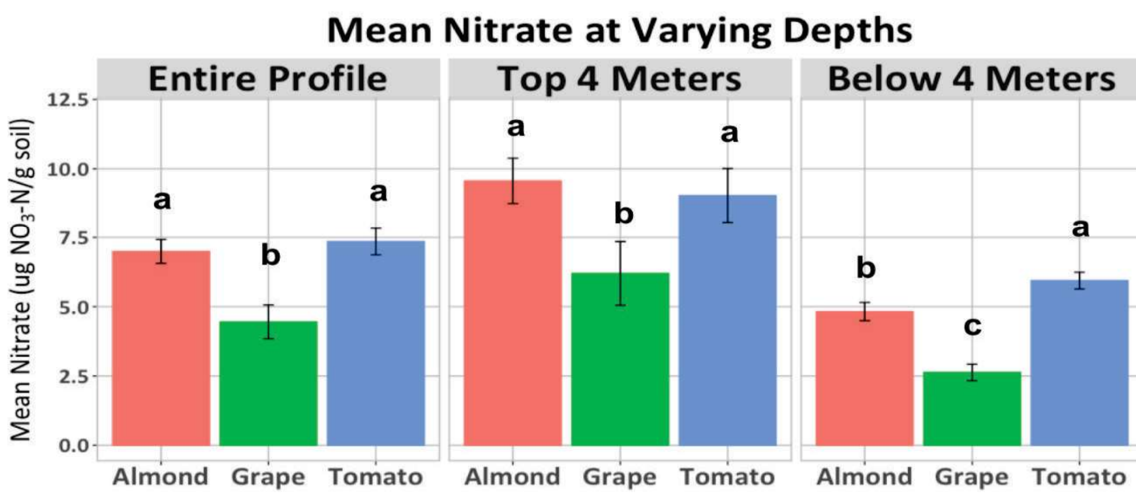
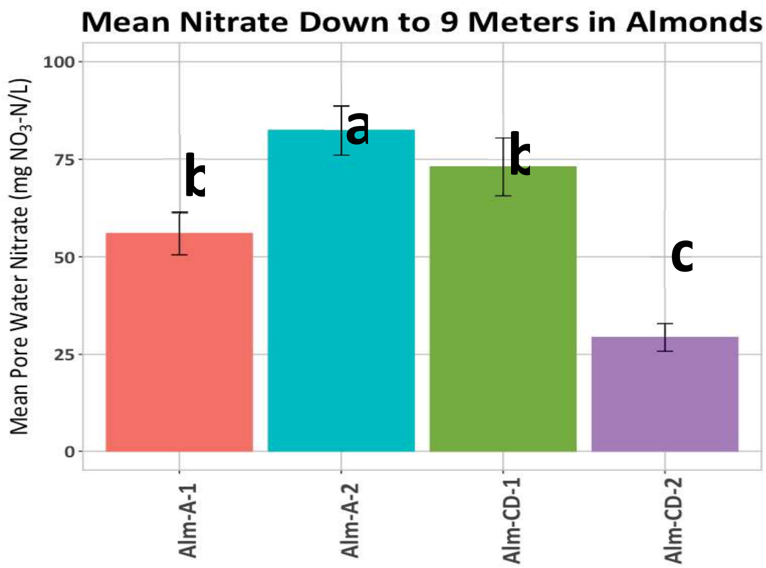
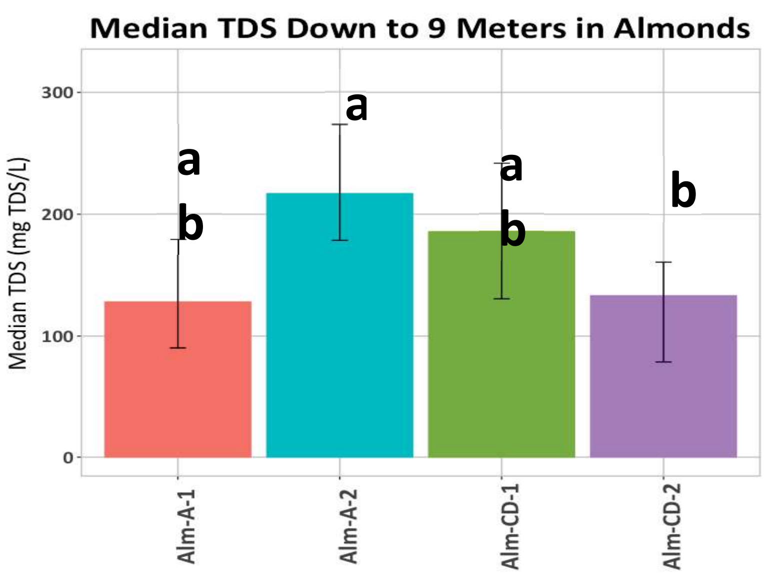


Figure 7. Farm Effects on Vadose Zone Chemistry

Vadose zone chemistry differed under different farmer management. Within almond cropping systems, Alm-A-2 had significantly higher pore water NO3 throughout the nine-meter profile, compared to Alm-A-1, Alm-CD-1, and Alm-CD-2, with Alm-CD-2 having the lowest concentrations. Across the nine-meter profile, TDS did not statistically differ across farms. However, when examining the data within almond cropping systems, TDS did vary by farmer with Alm-CD-2 having statistically lower TDS compared to Alm-A-2.



A. Nitrate.



B. TDS:

Use of data for modeling parameterization

Data from this study were used to parameterize the Hydrus model and to develop the Hydrus model inputs in several ways:

Nitrogen inputs: Nitrogen inputs from the different participating farmers were compared to other sources (e.g., UCD and CDFA guidelines; UC CE recommendations) in order to check the practices of the participating farmers against the industry (not outliers) and for estimating changes in N inputs over the last 25 years.

Texture and Lithology. Soil lithology was mapped for all the sampled cores as were NO3 concentrations in pore water. Comparing against all the lithological and NO3 profiles, four representative core classes were identified. For two of the 4 classes, a representative core was used for building the Hydrus 1D model. One core reflects finer soils and the other core reflects coarser soils. The effects of soil texture and lithology will be explored in the Hydrus model runs.

Nitrogen mass profiles. Nitrogen mass profiles were developed for each core and those profiles have been shown by crops and soil type (Figure 5). Those profiles were used to validate the Hydrus models. Those profiles were considered to be in steady state condition and reflect the variance in steady state conditions across a given crop (and soil type). For the Hydrus models, those profiles constrained the model. Models that produced N profiles inconsistent with general N trends were considered inadequate and efforts were made to correct.

Other Data Sources – Chowchilla Study

This study was designed to rely upon field soil cores and other data representative of steady state and did not include funding to assess changes in soil NO3 concentrations under OFFCR since availability of water for recharge could not be assumed during the project period. However, in 2016 when federal water was available, Sustainable Conservation provided additional funding to set up an OFFCR field trial on organic almonds[5] and purchase water for recharge. Soil cores collected at control (no recharge) and recharge treatment replicates in the orchard provided data used to help calibrate this project's modeling of NO3 flushing under OFFCR operations.

Next Steps

The results from this field study warrants further analyses of the data. That analysis is ongoing with the development of a peer reviewed publication under additional funding sources (e.g., Almond Board of California Grant, National Institute of Food and Agriculture, Tetra Tech, Bachand & Associates). These analyses are further exploring farm management and texture effects on soil N profiles and the potential impact on legacy transport of N under OFFCR.

Findings from this field study provide a stand-alone data set that can inform opportunities and constraints of OFFCR outside of its use in model development. Thus, these results will also be

[5] S. Bachand, S. Carlton and P.A.M. Bachand. 2017. On-Farm Flood Capture and Recharge (OFFCR) at an Organic Almond Orchard, Recharge Rates and Soil Profile Responses. Groundwater Recharge Project, 2016. Report to Sustainable Conservation, Sustainable Conservation, San Francisco, CA. In prep for publication.

used in informing interested parties and stakeholders (e.g. Water Boards, Groundwater Sustainability Agencies , farm groups) on the OFFCR practices.

III. Developing and Running Modeling Framework

Under this task, the integrated model earlier discussed under Task 2 (Figure 1) was developed and run. This section describes the key technical efforts and results associated with this task and identifies next steps.

Model Development

The Hydrus and Analytical Groundwater Model (AGM) were developed for this project. This section summarizes this process. More details will be available in a technical memorandum[1] serving as the draft for in-progress peer review publications.

Hydrus Model

Hydrus requires a defined vadose zone, the development of input files, and parameterization of the model. For the Hydrus model, two representative cores were selected from the field study that were found to be representative of lithological core classes for this study.

Fertilization and Irrigation Inputs

Fertilization and irrigation inputs were defined based upon a review of the literature. For fertilization, sources included input from participating farmers, University of California Cooperative Extension (UCCE) and the California Department of Food and Agriculture (CDFA). Irrigation inputs for each crop were defined by their ETc demand. California Irrigation Management Information System (CIMIS) at the Stratford Station (Station 15) were referenced to represent area evaporation needs. Crop specific ET rates (ETc) were developed using published crop coefficients (ABC 2017, Hanson et al 2006; Williams et al 2003, Snyder et al 2000), . Irrigation rates under the various practices were based upon an analysis of Application Efficiency (AE) for different regions and irrigation methods. AE measures irrigation system performance efficiency with regard to delivering a target irrigation depth for beneficial uses (Burt et al, 1997; Sandoval-Solis et al, 2013). Other beneficial uses aside from irrigation can be for salinity leaching, field preparation, microclimate control, weed germination or cover crop ET (Sandoval-Solis et al 2013, Canessa et al 2012). AE was used as a surrogate for Irrigation Efficiency (IE). IE represents a seasonal assessment tallying all beneficial uses, AE is event-based and assumes all water destined for a beneficial use will be used for those uses (Burt et al, 1997). If the targeted requirement is equal to the sum of all beneficial uses, AE provides a conservative estimate of IE if the beneficial uses are distributed uniformly across a field, acknowledging that unavoidable, nonbeneficial uses lower efficiency as does non-ideal scheduling (Burt et al 1997). The concept of AE was applied to assess the efficiency of water applied to a field meeting irrigation needs under two irrigation management scenarios: BAU, Business-as-usual; BP, Best Practices. Based upon that analyses, typical BP was estimated as 5% greater than ETc, and typical BAU was estimated as 10% greater than BP.

OFFCR Recharge Capacity, Rates, Frequency and Period

For this study, recharge rates of 15, 150 and 500 CFS are based on current ongoing efforts in the Kings Basin. These current efforts are effectively tangible models for implementation of this technology throughout the study area and the Central Valley in general. Terranova Ranch has conducted recharge in both 2012 (Bachand et al, 2011, 2014) and more recently in 2017 (LA

Times) at a recharge rate of about 15 CFS diversion rate from the James Bypass, limited by conveyance capacity and typical in capacity to other recent farm OFFCR efforts (TID 2017). The McMullin On-Farm Flood Capture and Recharge (OFFCR) Project funded through a California Department of Water Resources (DWR) Flood Corridor Grant, was begun in 2012 with the completion of the Hydrologic and Hydraulic Analyses (H&H) in January 2014, and CEQA in 2016 (Tetratech 2016a, b) and with design, permitting and agreements in process, and with construction planned to begin in 2018 (Monreal et al 2017). This project is currently being designed for a 150 CFS diversion capacity (Monreal et al 2017; KRCD 2012). The project is also planned for future expansion to a 500 CFS capacity (Bachand et al 2016) and current project design efforts are taking that expansion into consideration (Monreal et al 2017). This SCBG project modeled these OFFCR scale efforts, identifying appropriate acreage and predicted infiltration rates based upon previously published findings and relationships.[6]

All these recharge efforts are based upon infiltration rates measured under the NRCS CIG study used to test the hydrologic and logistical feasibility of OFFCR (Bachand et al, 2011, 2014). For the modeling purpose of this study, those measured infiltration rates are considered generally representative of much of the study area soils and changes in the recharge rates are primarily achieved through increasing acreage at an approximate ratio of 10 acres needed to capture and recharge 1 CFS (Bachand et al, 2011, 2014).

Groundwater Model

A 3-dimensional hydrologic and water quality analytical groundwater model (HW_qAGM-3DNS – Hydrologic Water quality Analytical Groundwater Model – 3D, Non-Steady State) was developed to simulate water quality effects on groundwater from vadose zone fluxes. More information is available on model development from Ung et al, 2017. Key points are summarized below.

HW_qAGM-3DNS is a 3-dimensional non-steady state analytical model based upon the fundamental equations describing saturated flow (Freeze and Cherry, 1979). Mass transport is modeled using advective-dispersion equations. The model was linked to Hydrus-1D such that hydrologic and water quality fluxes from Hydrus-1D would be inputs into HW_qAGM-3D. In this application, this model assumed conservative water quality transport. Neither NO3 or TDS were assumed to transform or degrade during groundwater transport.

A recharge area for a 10-mile x 10-mile watershed was defined for this study (Figure 9). Depending upon the recharge capacity, the soils and whether the lands were dedicated or rotational, the area varied. Under dedicated recharge on soils typical for the study area (Bachand

[6] Bachand, P.A.M., S. Roy, J. Choperena, D. Cameron and W.R. Horwath. 2014. Implications of Using On-Farm Flood Flow Capture To Recharge Groundwater and Mitigate Flood Risks Along the Kings River, CA. Environmental Science and Technology48(23), 13601-13609.

Bachand, P.A.M., W.R. Horwath, S. Roy, J. Choperena, and D. Cameron. 2011. Final Report: Implications of Using On-Farm Flood Flow Capture To Recharge Groundwater and Mitigate Flood Risks Along the Kings River, CA. For Grant Agreement No. 68-9104-0-128 between Bachand & Associates and the United States Department of Agriculture Natural Resources Conservation Service. September 30, 2012. http://aquaticcommons.org/11287/

et al 2011, 2014), approximately 150 acres are needed to divert 15 cfs, 1500 acres are needed to diver 150 cfs and 5000 acres are needed to divert 500 cfs.

Three monitoring locations were selected downstream of the recharge area. The recharge area used depended upon the capacity of the system being used. For each monitoring location, depths were selected to monitor groundwater quality representing a gradient through the production zone (Figure 3). CVSalts data were used to define general ambient groundwater quality conditions in the upper and lower groundwater zones. Ambient velocities and groundwater quality values are defined to represent the modeled area based on CVHM numerical flow model results in the Kings Subbasin region. Three ambient groundwater quality levels were selected based upon statistically analyzing the groundwater quality data in the upper and lower zones: 1) TDS = 250 mg/L and NO3-N = 2.5 mg/L; 2) TDS = 400 mg/L and NO3-N = 5 mg/L; and 3) TDS = 700 mg/L and NO3-N = 10 mg/L. These values represent the range of water quality distributions across the upper and lower zones, represent a more log-normal distribution, and are relevant to the regulatory limits for both NO3-N (10 mg/L, EPA 2006) and for TDS (500 mg/L secondary MCL,EPA 2014). Groundwater velocities were bracketed using high and low values representative of simulated velocities in the study area. These rates represent the range of observed horizontal and vertical velocities.

Model Outputs and Validation

Model outputs for both the Hydrus and groundwater models were identified by the project team as detailed in Figures 10 and 11. These outputs were a combination of graphical outputs and summary performance metrics. These outputs were used to 1) describe and quantify spatial and temporal hydrologic and water quality changes in the vadose zone and in groundwater and 2) to quantify temporal changes in flux from the vadose zone to groundwater under the different scenarios being tested, and Table 1. These outputs have also been used to compare model outputs to collected field data to assess model performance particularly in the model parameterization process and for the validation of the Hydrus model.

A variety of data were used to assess performance of the Hydrus model. Findings from the Chowchilla study have shown the expected amount of flushing that would be expected under low and high OFFCR rates.[Error! Bookmark not defined.] Those data were used to determine if Hydrus was modeling legacy flushing under OFFR. Nitrogen profiles from the soil core study (Data Collection for Model Calibration/Validation section) have provided a N profile range found in this study as typical for the different crops.

Nitrogen core profiles were qualitatively used to validate the Hydrus model (Figure 8), its inputs and parameters. This model validation has been, by necessity somewhat qualitative. The Hydrus model defines a model domain or universe which reflects human biases and assumptions. It is not possible to define the exact Hydrus model for this process given the limitations of the Hydrus model and the datasets available. Instead, significant effort and resources were invested to define a Hydrus model that will provide a reasonable representation of constituent and hydrologic transport through the vadose zone with respect to –

- the timing and magnitude of legacy flushing during the early periods of OFFCR,
- the mass of N and salts that will remain in the vadose zone over time,
- the effects to groundwater from different crops, land uses and practices,

- the effects to groundwater from the connectivity of surface water with groundwater under OFFCR, and
- other drivers of transport.

Ultimately, the Hydrus model will provide a reasonable tool for predicting the effects of OFFCR on the transport salt and nitrates through the vadose zone to groundwater, and for determining the potential impacts from changing agricultural and OFFCR management practices.

Use of the Analytical Groundwater Model for these purposes was not assessed.

Run Model for Scenario Testing and Characterization

Model runs have been ongoing with scenario testing to continue under funding from other projects. Some early data from the model runs are shown here. Figure 8 shows the cumulative NO3 profile in the 200-ft vadose zone under BAU conditions after a 25-year period. These modeled results show NO3 distribution in the vadose zone after historic farming operations. These model results are considered reasonable as they are in the range of NO3 profile concentrations measured in field soil core data collected from this study using the Geoprobe.

The Hydrus model was used to model the effects to groundwater under low and high volume recharge conditions similar to recharge conducted for field studies at Terranova Ranch and Chowchilla.[4, Error! Bookmark not defined.] The groundwater model was set up to observe locations at different distances and depths from the recharge location (Figure 9), enabling a spatial / temporal analyses of OFFCR effects on groundwater quality.

Figures 10 and 11 are examples of early groundwater runs. These runs model groundwater 2, 11 and 20 meter (6.5, 36 and 66 feet) below the groundwater/vadose zone interface at distances 2000, 6000 and 10,000 m (approximately 1, 4 and 6 miles) downstream of the recharge area. Groundwater responses are shown for low and high volume OFFCE (i.e., 2- and 10- feet annual recharge).[7] Under both these scenarios, water quality effects are most noticeable near the OFFCR area at the groundwater/vadose zone interface (shallow groundwater depths). The magnitude of the effects decrease with distance from the OFFCR area, with depth in groundwater and over time. In this example, ambient groundwater nitrate concentration is defined in these scenarios as 5 mg-N/L. Concentrations at the top of the groundwater near the OFFCR location initially increase by 40% and stay elevated over 30 years. For deeper groundwater locations (i.e. 11, 20 m; 36, 66 ft), and for locations further downstream (i.e. 6000, 10,000 m; approximately 4 and 6 miles), these effects are less and generally negligible. Groundwater quality effects are similar under both low and higher volume OFFCR scenarios. In this example, concentrations near the higher OFFCR location increase slightly more than under lower OFFCR levels but for the most part are very similar. These results suggest that the amount of recharge water is not the main driver for groundwater impacts, but the flushing of legacy

[7] Note early runs were used in model development, parameterization and validation. Current modeling efforts are looking at recharge efforts of 15, 150 and 500 CFS with infiltration rates of about 2 – 3 in/day (Bachand et al 2011, 2014). The rates of 2-ft and 10-ft are generally consistent with the recharge that would occur annually under dedicated recharge and rotating recharge.

constituents from the vadose zone as well as ongoing fertilization cultural practices may be the key drivers.

Next Steps

Further model runs are planned for next steps. The current project has provided a reasonable integrated vadose zone / groundwater model for use with various specialty crops studied here (tomatoes, almonds, grapes). The further runs will test the effects of the scenarios and management on groundwater quality and transport of nitrate and TDS to groundwater. Important findings will result from these runs including the following:

1. An estimate of N and salts remaining in the vadose zone under long-term OFFCR
2. The relative importance of ongoing fertilizer management with legacy constituents flushed from the vadose zone by OFFCR
3. The impact of increased surface water and groundwater connectivity that results from OFFCR on groundwater quality
4. Reasonable estimates of timing regarding the time for constituents to be flushed from the vadose zone and the time for that initial pulse to dissipate spatially.
5. The impact on groundwater quantity and quality across the production zone.
6. An understanding of potential pumping effects on groundwater quality, both temporally and spatially.

Table 5.Modeling Outputs

Model outputs identified for both the Hydrus and groundwater models are provided in the table. These outputs are a combination of graphical outputs and summary performance metrics. These outputs are used 1) to describe and quantify spatial and temporal hydrologic and water quality changes in the vadose zone and in groundwater and 2) to quantify temporal changes in flux from the vadose zone to groundwater under the different scenarios being tested. These outputs have been also used to compare model outputs to collected field data to validate the Hydrus model, particularlyduring the parameterization process and .
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			Unit	Graphs	Files/ Spreadsheets
Groundwater					
	Temporal Graphs and spreadsheets by time				
		NO3-N & TDS levels by detph (t)	NO3-N mg/L; TDS mg/L	Selected locations/ runs/depths	Selected locations/ runs/depths
		Avg NO3-N & TDS in production zone(t)	NO3-N mg/L; TDS mg/L	All	All
	Summary performance metrics				
		Time of run	y or days	NA	All
		Total time above 10 mg/L at each depth	y or days	NA	All
		NO3-N and TDS average during time to steady state at each depth	NO3-N mg/L; TDS mg/L	NA	All
		Time to steady state	y or days	NA	All
Vadose Zone					
	Descriptive				
		NO3-N & TDS profile with depth in vadose zone	mg/kg	Selected years	Selected years
so		water flow and NO3-N & TDS mass fluxes		Selected years	Selected years
	Temporal Graphs and spreadsheets by time				
		water flux	volume per year		All
		vadose zone NO3 and TDS mass over time	NO3-N, TDS (kg)		All
		N & TDSapplied(t)	NO3-N, TDS (kg)		All
		N & TDS exported to groundwater(t)	NO3-N, TDS (kg)		All
		N & TDS exported past root zone (t)	NO3-N, TDS (kg)		
		% NO3-N & TDS exported to groundwater(t)	%		All
		% NO3-N& TDS exported past rootzone (t)	%		
	Summary performance metrics				
		Initial Vadose zone mass post BAU	NO3-N, TDS		
		Final vadose zone mass post BMPs/recharge run	NO3-N, TDS		
		Time to steady state	y or days		All
		Time of run	y or days		All
		Cumulative N applied by steady state	NO3-N kg		All
		Cumulative N exported by steady state	NO3-N kg		All

Figure 8. Modeled Cumulative N Profile for different crops

Hydrus model outputs were developed for the different specialty crops. Soil profiles were developed over a 25-year run under BAU fertilization and irrigation practices. Nitrogen profiles are shown for a 200-foot unsaturated (vadose) zone showing cumulative N mass by depth. The profiles show increasing N with depth over the 25-year period and compares those profiles with the first 30-feet of data from collected soil cores.

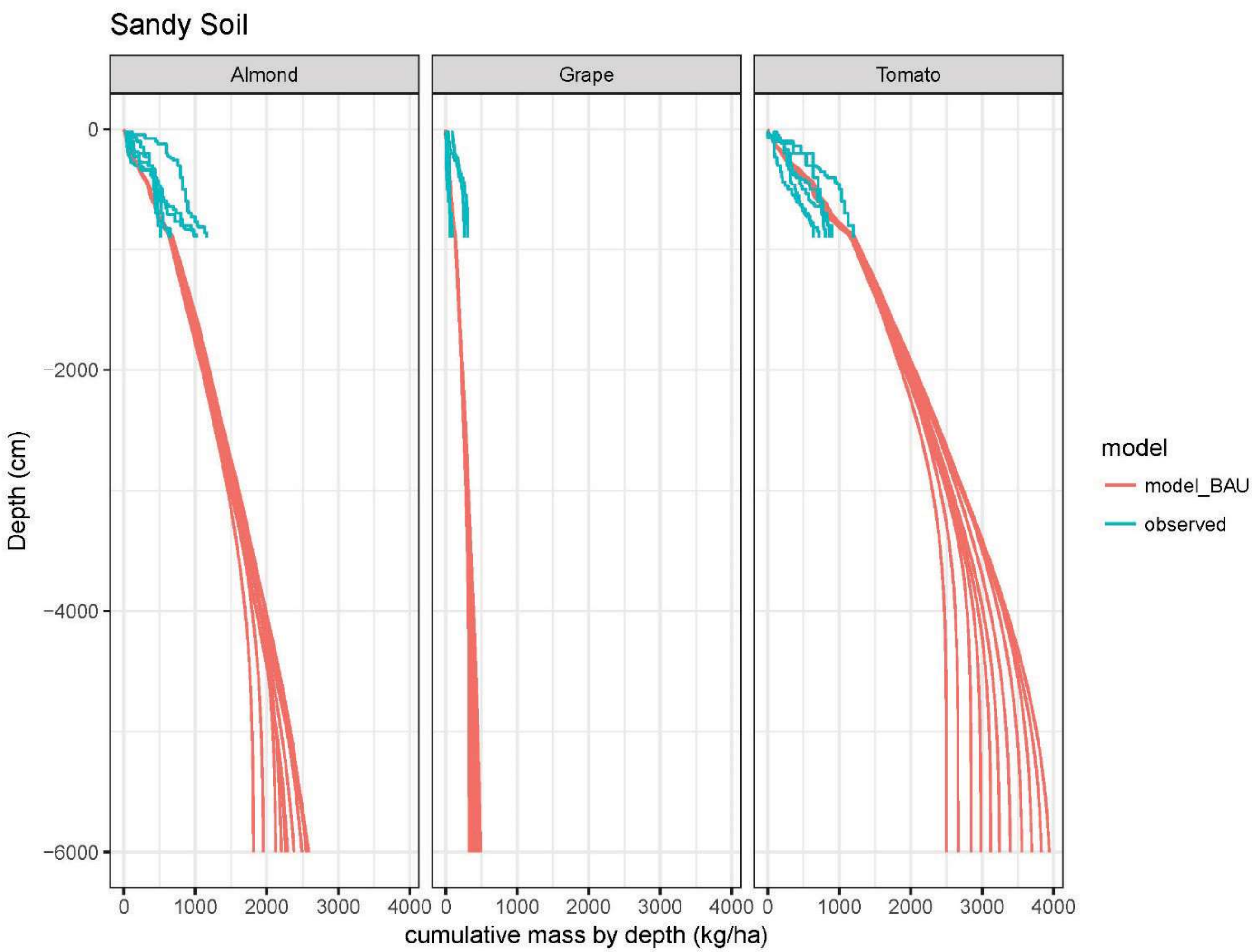

Figure 9. Boundary condition geometry and observations points
Locations represent observation points downstream of the OFFCR area. At each observation point, simulated groundwater is sampled at observed depths below the groundwater / vadose zone interface. These depths can be varied, as well as the observation points. At each location, groundwater quality can be monitored over time.

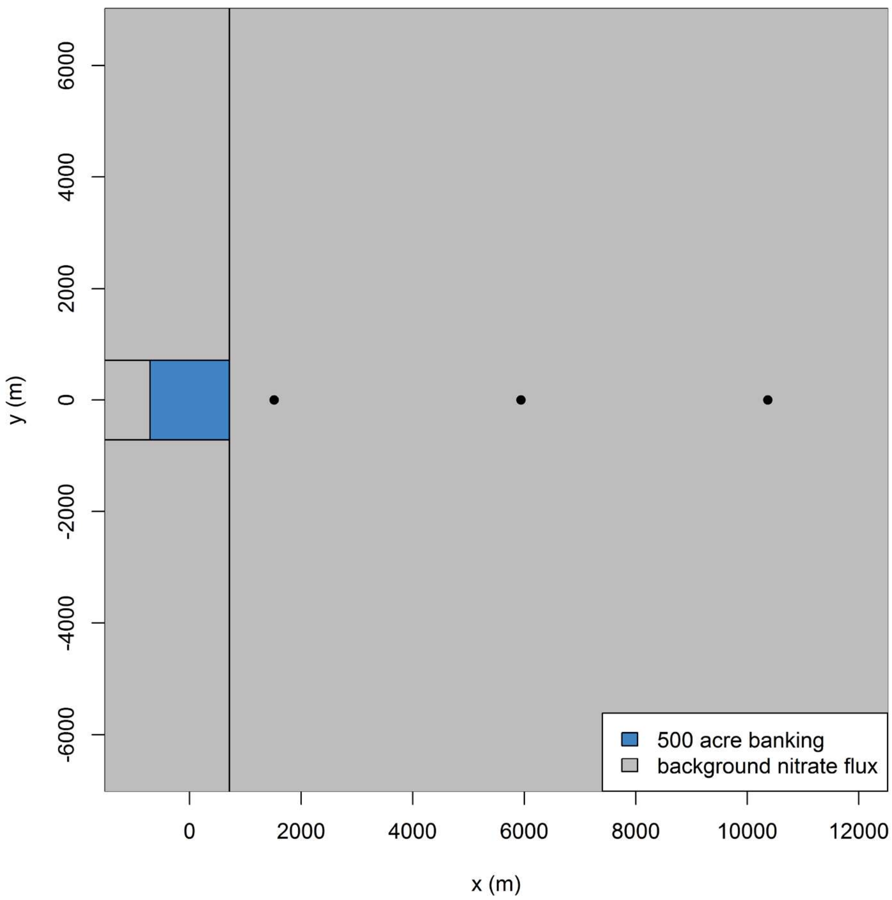

Figure 10.Changes in groundwater nitrate concentrations under low OFFCR rates.

This example is representative of lower recharge rates (2-ft recharge per recharge year) across 500 acres for groundwater velocities in the range typical for the Tulare Lake Hydrologic Region (Vx = 2 ft/d, Vz = 0.003 ft/d). Locations represent observation points downstream of the OFFCR area (2000, 6000, 10,000 m; approximately 1, 4 and 6 miles) at depths of 2, 11 and 20 m (6.5, 36 and 66 ft) below the groundwater/ vadose zone interface. Groundwater quality effects are most noticeable near the OFFCR area at the first-encountered groundwater, or near where the groundwater/vadose zone interface occurs. The magnitude of the effects decrease with distance from the OFFCR area, with the depth of groundwater sampled, and over time. Ambient groundwater concentration are defined here as 5 mg-N/L In this example, concentrations near the OFFCR location increase by 40% and stay elevated over 30 years due to continued leaching and transport of nitrate with ongoing OFFCR at the recharge site. For deeper locations, and for locations further downstream those effects are less and can effectively be negligible.

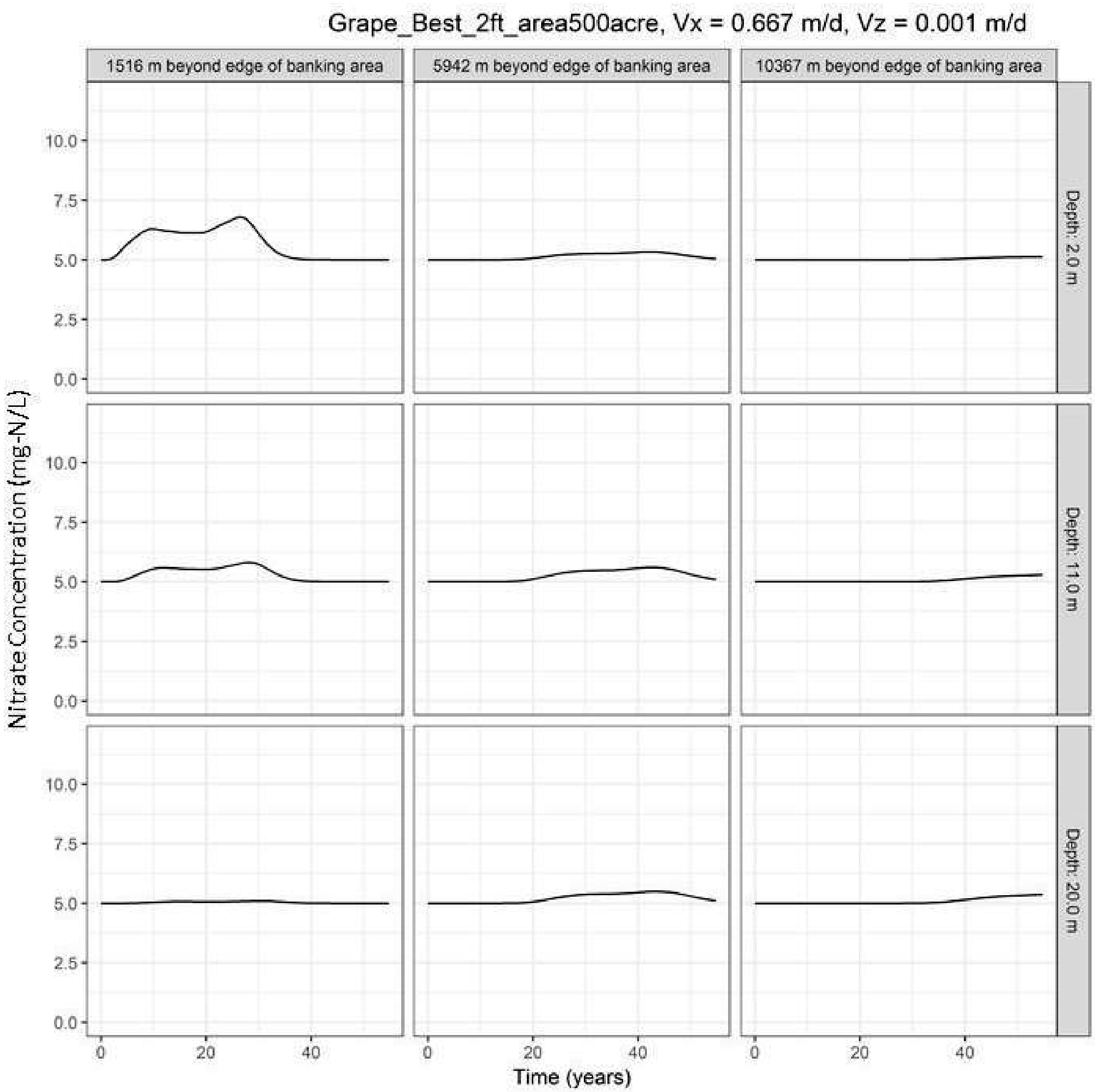

Figure 11. Changes in groundwater nitrate concentrations under higher OFFCR rates.
This example is representative of higher recharge rates (10-ft recharge per recharge year) across 500 acres for groundwater velocities in the range typical for the Tulare Lake Hydrologic Region (Vx = 2 ft/d, Vz = 0.003 ft/d). Locations represent observation points downstream of the OFFCR area (2000, 6000, 10,000 m; approximately 1, 4 and 6 miles) at depths of 2, 11 and 20 m (6.5, 36 and 66 ft) below the groundwater/ vadose zone interface. Groundwater quality effects are most noticeable near the OFFCR area at the first-encountered groundwater, or near where the groundwater/vadose zone interface occurs. The magnitude of the effects decrease with distance from the OFFCR area, with the depth of groundwater sampled, and over time. Ambient groundwater concentration are defined here as 5 mg-N/L In this example, concentrations near the OFFCR location increase slightly more than under lower OFFCR levels but for the most part are very similar. This figure suggests that the amount of recharge water is not the main driver for groundwater quality impacts but also the flushing of legacy constituents from the vadose zone as well as ongoing fertilization cultural practices.