Almond Field Study
Phase 2: Draft Conceptual Plan

Preliminary Draft

January 2016

Subject to Revision

SAN JOAQUIN RIVER
RESTORATION PROGRAM

This page left blank intentionally.

Table of Contents

Table

Figures

Attachment

List of Abbreviations and Acronyms

ac	acre
Act	San Joaquin River Restoration Settlement Act
Cal Poly	California Polytechnic State University, San Luis Obispo
cm	centimeter
CVP	Central Valley Project
FWA	Friant Water Authority
g	grams
GPS	global positional system
lb	pound
meq	milliequivalents
mmhos	millimhos
NRDC	Natural Resources Defense Council
PG	Parcel Group
ppm	parts per million
RWA	Recovered Water Account
SCTFG	Seepage and Conveyance Technical Feedback Group
Secretary	United States Secretary of the Interior
SJRRP	San Joaquin River Restoration Program
SMP	Seepage Management Plan
SWRCB	State Water Resources Control Board
UC	University of California
USDA	U.S. Department of Agriculture

This page left blank intentionally.

1.0 Background

In 1988, a coalition of environmental groups, led by the Natural Resources Defense Council (NRDC) filed a lawsuit, known as NRDC, et al., v. Kirk Rodgers, et al., challenging the renewal of long-term water service contracts between the United States and the Central Valley Project (CVP) Friant Division contractors. On September 13, 2006, after more than 18 years of litigation, the Settling Parties, including NRDC, Friant Water Authority (FWA), and the U.S. Departments of the Interior and Commerce, agreed on the terms and conditions of a Settlement subsequently approved by the U.S. Eastern District Court of California (Court) on October 23, 2006. The San Joaquin River Restoration Settlement Act (Act), included in Public Law 111-11 and signed into law on March 30, 2009, authorizes and directs the Secretary of the Interior (Secretary) to implement the Settlement. The Settlement establishes two primary goals:

- Restoration Goal – To restore and maintain fish populations in “good condition” in the main stem San Joaquin River below Friant Dam to the confluence of the Merced River, including naturally reproducing and self-sustaining populations of salmon and other fish
- Water Management Goal – To reduce or avoid adverse water supply impacts on all of the Friant Division long-term contractors that may result from the Interim and Restoration flows provided for in the Settlement

To achieve the Restoration Goal, the Settlement calls for releases of water from Friant Dam to the confluence of the Merced River (referred to as Interim and Restoration flows), a combination of channel and structural modifications along the San Joaquin River below Friant Dam, and reintroduction of Chinook salmon. Restoration Flows are specific volumes of water to be released from Friant Dam during different water year types, according to Exhibit B of the Settlement and began on January 1, 2014. The Water Rights Order dated October 21, 2013 is a long-term authorization to modify Reclamation's water rights to implement Restoration Flows. Interim Flows were experimental flows that began in 2009 and continued until Restoration Flows were initiated, with the purpose of collecting relevant data concerning flows, temperatures, fish needs, seepage losses, recirculation, recapture, and reuse, pursuant to Order WR 2009-0058-DWR from the State Water Resources Control Board (SWRCB) and continued under Orders WR 2010-0029-DWR and the Order dated September 30, 2011.

Both Condition 7 of the long-term Water Rights Order and Environmental Commitments EC-7 and EC-8 of the San Joaquin River Restoration Program (SJRRP) Programmatic Environmental Impact Statement / Environmental Impact Report require compliance with the Seepage Management Plan (SMP) for release of Restoration Flows. Reclamation developed the SMP to: (1) limit Interim and Restoration Flows to reduce or avoid material adverse groundwater seepage impacts through setting thresholds in over 200 groundwater monitoring wells, and (2) to identify a process to increase flows through construction of seepage projects. The seepage control projects may include a variety of realty (i.e., non-physical) and/or physical actions.

The SMP includes the methods to ensure that agricultural lands adjacent to the SJRRP area are not adversely affected. Root zone depth of crops and field conditions that affect them, such as capillary rise of water from depth, are an integral part of this determination; however, there is little scientific literature from which the range of crop root zones and capillary fringe, especially those of tree crops, can be determined in a specific area such as the SJRRP project area. This lack of documented information on root zones is largely because of the difficulty, time and expense associated with studying tree roots and associated field conditions in situ.

Therefore, scientific information that gave broad guidelines and stakeholder input were used as sources of almond root depth estimates. These estimates represented a range of almond root depth.

2.0 Introduction

In an effort to develop a further understanding of almond root zone characteristics, Reclamation initiated a two-phased Almond Root Zone Study. Phase 1 was conducted in summer of 2015 and is briefly summarized below. A potential outline for Phase 2 of this study, a field investigation) is described in this conceptual plan. While this document proposes several investigation types and methodologies, Reclamation may or not move forward with Phase 2. The execution of Phase 2 will be discussed and planned in collaboration with stakeholders to ensure any proposed work is both useful and acceptable to all parties.

2.1 Phase 1 Study Results

Phase 1 of the Almond Root Zone Study was conducted in summer of 2015 and included a literature review and consultation with University of California (UC) researchers and Cooperative Extension agents on almond tree growth, tree roots, and impacts of water and salinity on root systems. The results of the Phase 1 Study indicated that there is general consensus on almond root zone depth, and on the different types of roots and where they reside in the soil. The Phase 1 report, *Almond Root Zone Study Plan, Phase 1* (Administrative Draft, June 2015) documented the information collected in this phase of study. This report was posted to the SJRRP website for public comment (http://www.restoresjr.net/wp-content/uploads/Phase-1-Almond-Root-Zone-Study-Plan-Admin-Draft-20150629.pdf). The report findings were also presented at the Seepage and Conveyance Technical Feedback Group (SCTFG) meeting help on August 6, 2015 in Los Banos, California. The SCTFG meeting presentation is available on at: http://www.restoresjr.net/get-involved/technical-feedback-meetings/seepage-and-conveyance/.

Phase 1 findings and input from stakeholders also indicated that though there is general consensus on almond root zone depth, the depth threshold in the SMP used to protect almond roots from seepage impacts must also include an allowance for capillary rise - the upward movement of water from water tables that may allow saline water to enter the root zone of almonds. The upper limit of this capillary movement, called the capillary fringe, is highly variable between soil textures, sites with different groundwater levels, years and seasons. Though capillary fringe was addressed in the SMP, there may be a current need to refine estimates of capillary fringe in the project area.

2.2 Phase 2 Study Draft Concepts

This document provides Reclamation's potential concepts for implementing Phase 2 of the study. This Conceptual Plan presents two potential topics of study in the following sections:

- Almond Root Zone: Section 3 focuses on characterization of almond root depth within the SJRRP area
- Capillary Fringe: Section 4 focuses on further refining our understanding of capillary rise in the SJRRP area

These two study topics are neither mutually inclusive nor exclusive. Reclamation and participating stakeholders may collaboratively determine that one, none, or a combination of some concepts from both plans are desired. Both of the options incorporate information gained through literature review and expert interviews in the study Phase 1, and would also take into consideration input from cooperating growers and stakeholders.

The Phase 1 work indicated that almond root depth is influenced by soil type, soil moisture regime, salinity, rootstock, and orchard density. Therefore, the almond root zone study concepts have been designed to account for these variables found within orchards. Similarly, capillary fringe is dependent on certain soil and site conditions, and as such, can only be represented well in the project area by taking these site characteristics into account.

This conceptual plan includes discussion of draft concepts for both topics of field study, including preliminary recommendations for study design, methodology, site selection criteria, and tasks. However, the conceptual study components are not complete and include various levels of detail depending on the amount of background information obtained on each topic during Phase 1 efforts. More preliminary work was done in Phase 1 to inform an Almond Root Zone Study. The capillary fringe topic arose out of Phase 1 efforts as an important topic potentially warranting additional Study. However, less preliminary work has been completed to inform the study concept for capillary fringe. Therefore, expert and stakeholder input would be important in refining an approach for this potential study.

3.0 Conceptual Plan for Almond Root Zone Field Study

The two study topics described in Sections 3 and 4 are neither mutually inclusive nor exclusive. Reclamation and participating stakeholders may collaboratively determine that one, none, or a combination of some concepts from both topics are desired. Both of the options incorporate information gained through literature review and expert interviews in the study Phase 1, and would also take into consideration input from cooperating growers and stakeholders.

3.1 Purpose and Objectives

The primary purpose of this field study would be to verify and/or refine almond root zone depths in the SJRRP area. The study approach seeks to characterize the range of variability in root zone depth by gathering root zone data from orchards within a range of soil conditions representative of the SJRRP area.

The objectives of the Phase 2 Almond Root Zone study are:

- Validate root zones and their respective root densities and types, as anticipated by UC experts and scientific literature;
- Characterize specific root depths within soil conditions typical of SJRRP area and seepage parcel groups; and
- Provide quantitative support for the almond root zone threshold specified in the SMP.

3.2 Approach

The approach to the field study was informed by Phase 1 results, during which pertinent scientific literature and up-to-date information from UC research and extension experts on almond tree growth, tree roots, and impacts of water and salinity on root systems were gathered. Experts were consulted to gain knowledge specific to San Joaquin River riparian almond culture, and a literature review was conducted for general information on factors that influence root growth. With this information, the project area was evaluated qualitatively to determine what commonalities and differences exist within properties considered for potential almond root zone field investigation. These identified commonalities and differences resulted in soil categories that are considered in this preliminary plan.

The conceptual approach seeks to balance time and cost efficiency with a desired level of detail for field data. This would include selecting sites representing selected site condition categories, rather than sampling every PG. The advantage of this approach is that it represents all of the environmental site condition factors determined to be primary influences on root growth (soil texture, salinity and water table depth), while avoiding having to sample every site. The Phase 2 Almond Root Zone Study concept includes three main components:

1. Grower coordination and involvement in refining study parameters;
2. Main field study; and
3. A small scale pilot/verification test of the coring methodology to insure it adequately captures desired information on the root zone.

Each of these components of study is discussed in the sections that follow.

3.3 Grower Coordination and Involvement

Grower coordination would be important for reviewing and refining study objectives, gaining input on the study plan, as well as verifying study site locations and access. This would be accomplished through public meetings and/or direct contact with growers. During this step, background data would also be collected for each of the sites to be evaluated. Information about site conditions and almond production would be collected including:

- Orchard age and history;
- Rootstock;
- Variety;
- Irrigation methods and methods; and
- Other site specific practices or characteristics/challenges.

The results from this effort would be used to finalize a study implementation plan including study site locations.

3.4 Main Field Study

The Root Zone Study would be centered on observation of roots using some form of excavation, mainly soil coring, at a number of almond orchard sites located within the SJRRP area. The conceptual design takes into account variability between almond orchards and spatial variability within orchards, as it affects root depth. The level of site replication preliminarily recommended is balanced between capturing this variability, collecting a robust dataset, and keeping the cost associated with higher replication feasible.

3.4.1 Site Selection

The criteria for site selection are focused on variables that influence root growth as well as other factors related to cultural practices and landowner cooperation. Anticipated site selection criteria are listed below.

- Orchard age – Orchards of at least eight years old would be targeted and are expected to represent mature root systems.

- Cultural practices – Site selection would consider cultural practices typical of the region (e.g., irrigation methods, tree spacing, etc.) to ensure the sites are representative of typical almond production.

- Preexisting salinity or groundwater monitoring data – Suitable sites located near previous salinity or groundwater monitoring locations may be preferential for data comparisons and added richness in the study dataset.

- Proximity to river or modeled flow threshold – Orchards located near potentially higher groundwater conditions may be preferred to observe impacts of shallower ground water and/or capillary fringe conditions.

- Spatial distribution – Site should be distributed across the spatial extent of the SJRRP area in order to represent a range of spatial conditions.

- Site accessibility/previous environmental clearance – Sites should be located near access roads or farm roads to allow access for field study. In addition, suitable sites near points with previous environmental clearance may be preferred to reduce the degree of permitting effort that may be required.

- Inclusion of multiple trees/rows to allow for final tree selection – Sites would consisted of an area within an orchard (rather than a single point) that contains several trees and multiple tree rows to allow for final selection of trees in the field at the time of study implementation. This would help to avoid unusual site characteristics that may exist but not be evident until the time of study (e.g., a broken micro sprinkler or atypical tree).

- Soil type - This study should include investigations that cover the range of soil types expected in the SJRRP area. Soils within priority PGs were evaluated and categorized into six categories representing that best represent the range of conditions, based on review of soil survey information and boring logs throughout the study area (Table 3-1). To capture variability within each given category and strengthen study findings, three to six sites were selected within each soil category. This approach would allow the characterization of a range of conditions among PGs and realizes efficiencies in time and cost by grouping site conditions. Where possible, to minimize new site impacts, sites were collocated within a 100-foot buffer of existing monitoring wells which have had previous environmental clearance efforts and also were within or adjacent to suitable almond orchard locations.

Table 3-1.
Soil Category Descriptions

Soil Category	Description
1	Non-saline, course to medium textured soils
2	Saline, course-textured soils
3	Saline loamy, or medium textured soils
4	Non-saline, fine-textured soils
5	Saline fine-textured soils
6	Restrictive (including hardpans or subsurface clay layers) or stratified soils

Study sites would represent areas (varying in size) that encompass multiple almond trees. Figure 3-1 shows an example area of a study site. The specification of a study area rather than a single point allows for study sampling efforts to be adjusted within each area based on field conditions to avoid anomalous conditions (e.g., leaking irrigation lines, declining tree, etc.).

Figure 3-1.
Example Study Site Area

3.4.2 Main Field Study Methods

The most comprehensive method to observe root zone depth and characteristics would be through actual excavation of tree roots, at least partially, to determine root presence or absence. Multiple excavation methods were reviewed during Phase 1 study efforts. Based on that review, partial root excavation using hydraulic soil core sampling (with a core diameter of 3.25 inches) would be recommended as a preferred method for this study. This method would be recommended for the following reasons:

- There are minimal safety concerns;

- Equipment required can operate in densely planted orchards with full canopy without significant damage to the canopy;
- Excavation to a depth of 10 to 15 feet depth is feasible, safe, and relatively quick;
- Root damage is limited and trees need not be destroyed;
- The location of individual cores can be adjusted in the field if necessary based on the subsurface conditions encountered (e.g., hardpan, cobbles); and
- Several cores can be taken at a given tree in a relatively short period of time to achieve the desired sample size.

The coring method is expected to provide the most information within reasonable cost and time parameters, while limiting risk to field staff and orchard damage. Other excavation methods reviewed were either inadequate for certain soil conditions, or were more costly and/or destructive.

Core Excavation

Each site would be evaluated by extracting and sampling a series of soil cores. Root development and prevalence is known to be impacted by proximity to both the trunk and irrigation water distribution. Therefore, between five and 10 soil cores would be sampled within each site to capture variability in root depth and characteristics at a series of locations relative to the tree and irrigation system. Because tree spacing and irrigation configuration vary by site, the exact locations of the cores would be selected in the field. Figure 3-2 provides one example of a possible schematic for core placement.

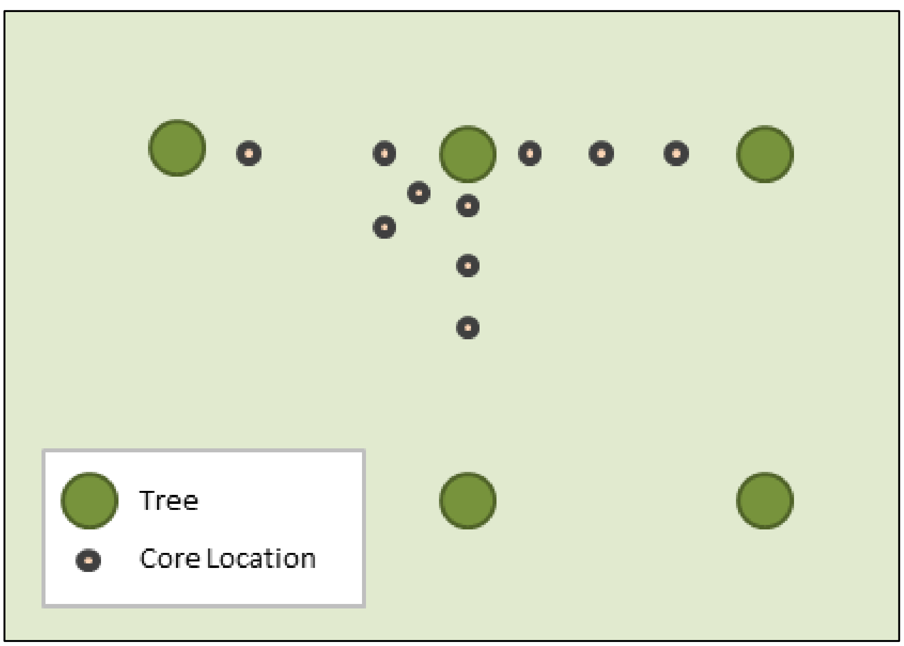

Figure 3-2.
Example Layout of Core Locations within a Study Site

Subsurface soil cores can be extracted using a hydraulic coring device mounted to a small diesel powered tractor, such as the Geoprobe hydraulic probe shown in Figure 3-3. With this device, cores up to 3.25 inches in diameter can be extracted to a depth of 14 feet. Excavation depths for each core would depend on the root depths encountered but would likely exceed five feet to fully characterize the root systems.

Figure 3-3.
Tractor Mounted Hydraulic Probe (Geoprobe 6610 DT)

Core Soil and Root Characterization

The soil cores would be examined using U.S. Department of Agriculture's (USDA) soil characterization criteria for root and soil characteristics. Cores would be evaluated for root presence, size, prevalence and type, and density of roots in varied size classes by depth Soil characteristics such as physical properties, stratification, and moisture could also be logged.

3.4.3 Equipment

The following equipment would be proposed to implement the methods described above:

- Field truck for transporting field personnel, soil samples, and other equipment;
- Tractor-mounted hydraulic probe for extracting cores for root observation;
- Safety equipment, such as hard hats, safety glasses, etc.;
- Shovels and hand soil excavation equipment for observing soil profile characteristics;

- Munsell soil color evaluation book for determining soil color including redoxomorphic features and indicators of gleying, etc.;
- Sample bags and boxes to collect and store soil samples;
- GPS and camera for logging tree locations and recording soil profile and root observations; and
- Soil moisture meter and or soil matric potential meter for field soil moisture status measurement.

3.5 Methodology Validation

Because soil coring has not been widely used in this region for root observation, a pilot trial of the core equipment would be recommended. A series of two to four of the study sites would be characterized in this pilot effort to verify the feasibility of the excavation approach.

It would also be recommended that, at up to two sites, one more extensive backhoe excavation would also be conducted in order to verify the core-based root observation methodology. At these sites, a portion (less than 25 percent) of the root zone would be excavated to a limited depth to observe roots and compare with collocated coring results. Figure 3-4 shows an example of a backhoe pit configuration for this purpose. The dimensions of the pit are expected to be approximately four feet by eight feet, with further areas sloped back to comply with safety requirements (Figure 3-4).

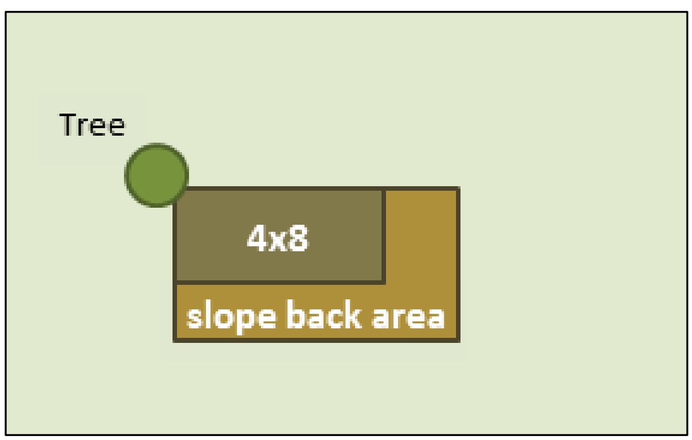

Figure 3-4.
Example Layout of Backhoe Excavation at Selected Tree

Evaluating and sampling soil from the backhoe pits for the same parameters as the core excavations (see previous sections) would verify results of the core sampling method. Personnel would coordinate with growers in the selection of representative trees for this effort within two of the study sites that are easily accessible with the required equipment.

This page intentionally left blank.

4.0 Conceptual Plan for Capillary Fringe Field Study

As mentioned above, the two study topics described in Sections 3 and 4 are neither mutually inclusive nor exclusive. Reclamation and participating stakeholders may collaboratively determine that one, none, or a combination of some concepts from both topics are desired. Both of the options incorporate information gained through literature review and expert interviews in the study Phase 1, and would also take into consideration input from cooperating growers and stakeholders.

4.1 Purpose and Objectives

The primary purpose of the capillary fringe study would be to further the understanding of capillary fringe in different site conditions within the project area. The study approach seeks to characterize the range of variability in capillary fringe to provide a more complete representation of capillary fringe in the SJRRP area.

The objectives of the Phase 2 Capillary Fringe Study are:

- Gather more information on the nature, extent and study methods of capillary fringe;
- Evaluate existing data and identify data gaps that need to be addressed;
- Design a field and/or lab study to address these data gaps; and
- Develop specific guidelines for the range of capillary fringe in various soils and site conditions, to be used in conjunction with root depth estimates to protect almond roots from seepage in the project area.

4.2 Approach

The approach to the capillary fringe conceptual field study plan was informed by (1) review of existing data from previous field investigations conducted by Reclamation staff; (2) review of a California Polytechnic State University, San Luis Obispo (Cal Poly) capillary fringe study in the project area; and (3) a literature review on the nature, extent and methods of study of capillary fringe.

The Capillary Fringe Study includes four main components for implementation:

- <u>Literature review</u> to gather information on (1) the nature and extent of capillary fringe in field soils and (2) methods of studying capillary fringe in the field and in the laboratory;

- Evaluation of existing data and identification of data gaps including review of data collected during previous field investigations in the project area, such as groundwater monitoring well boring logs, EM38 data, capillary fringe observations, soil data and any other pertinent field data; and
- Development of study method to address identified data gaps in a project-specific study.

Each of these components of study is discussed in the sections that follow.

4.3 Literature Review

The literature review for the Almond Root Zone Study was presented in Phase 1, as described in Section 1; however, no background information on capillary fringe has been presented to date. The literature review on capillary fringe, though a smaller effort, was conducted for the purpose of providing some guiding information for this conceptual plan. The specific objectives of the literature review were as follows:

- Define capillary rise and capillary fringe as it is described in scientific literature;
- Summarize findings on:
  - Characteristics of capillary fringe;
  - Influences on capillary fringe;
  - Typical heights of capillary fringe in fine soil types;
  - Spatial and temporal variability of capillary fringe; and
  - Methods used to measure capillary fringe in the field along with their accuracy, feasibility, applicability in various soils, etc.;
- Determine applicability of existing data to interpretations in current literature; and
- Recommend potential approaches to refine estimates of capillary fringe specified in current SMP protocols.

4.3.1 Key Literature Review Findings

The key findings of the literature review are summarized below. A more detailed summary of the literature review on capillary fringe is included in Attachment A.

- The definition of capillary fringe has differed among experts for decades. It is more commonly defined as the tension-saturated zone, while some define it as a transition zone between the water table and the unsaturated zone, which includes water content that varies from essentially saturated to whatever the content is when it meets water infiltrating from above. Therefore, it is important to clarify what definition of capillary fringe is assumed when capillary fringe values are reported.
- Capillary rise is defined as the movement of pore water against the flow of gravity. Capillary rise depends on: soil type; soil moisture depletion in the root zone; depth to the water table; and recharge. The zone of tension saturation

typically referred to as the capillary fringe is discrete or "compact," meaning that soil moisture decreases abruptly above its upper limit.

- Typical capillary fringe in fine soils is estimated up to several yards in several sources. These estimates of capillary fringe are observed in labs or modelled, but may not represent field conditions. Estimates of capillary fringe in SMP are generally lower than reference sources.
- Capillary rise varies spatially and temporally within relatively short distances (a few feet) and seasons.
- Capillary rise can be measured in the field with portable soil moisture instruments that measure in situ soil moisture, or by extracting cores and conducting measurements on them. However, soil moisture measurements must be related back to saturation percentage to determine what level of saturation is present in a particular soil. Portable instruments that measure soil water content are convenient but precision is questionable, especially in some soil types. Capillary fringe has been measured using coring techniques proposed in the Almond Root Zone Study Plan (Phase 2) and other common soil property measurements.

4.4 Data Review

Reclamation has conducted numerous field studies to collect various types of data on project soils, site conditions, and groundwater levels in addition to direct observations of capillary fringe. Monitoring continues to provide pertinent data, and this data should be used where possible to minimize study development efforts. This effort is an integral step in focusing the study to ensure that previous observations are not duplicated and the study yields meaningful data.

Appendix H of the SMP describes in detail the procedure that was used to determine and observe capillary fringe. This part of the SMP also includes summarized results of these findings. While these findings are still valid, there would likely be an opportunity to further evaluate and expand upon the representativeness of these findings with additional field data. For example, many of the capillary fringe observations were limited by the level of the groundwater at the time of the field work.

In this effort existing data would be reviewed including previous capillary fringe observations and project area soil conditions observed within the depth range of interest. The raw data associated current SMP capillary fringe estimates would be evaluated further based on a broader range of soil textures and conditions. Soil data would be assessed to identify soil/site conditions that are not well represented by current capillary fringe data. These conditions would be those targeted in capillary fringe study efforts in order to build upon the current data and improve the understanding of capillary fringe in the project area. The results of this effort would guide field study development so that resources are spent on collecting the most meaningful data.

4.5 Study Method Development

Study Method development would focus on soil/site conditions identified in data review efforts that are not well represented by current capillary fringe data. Depending on the spatial distribution and conditions within such areas, a study approach would be designed to better characterize the associated capillary fringe.

It is anticipated that multiple approaches may be required to characterize capillary fringe where site conditions are not suitable for field observations. A bench scale test in which conditions are imposed may be needed.

The study concept for capillary fringe would be centered on observation and instrumental measurement of relative soil moisture and capillary fringe using one or more proven methods. Some methodology options are presented in Section 4.5.1, each with its advantages and disadvantages. While the field study would ideally capture the variability of capillary fringe between almond orchards, ideal site conditions may not be found for every soil type at the time the study is conducted. For example, groundwater levels, which fluctuate seasonally, may not be found at the desired depths (preliminarily estimated at 2 to 10 feet below the effective root zone) for all soil types when field work would occur. Therefore, a combination of approaches may be appropriate.

4.5.1 Capillary Fringe Study Methods

A number of field study methods are possible (see literature review summary in Attachment A), including:

1. Laboratory soil column methods;
2. Field methods using portable instruments to make measurements directly where conditions are suitable;
3. Methods that combine basic soil property measurements from field soil samples to indirectly determine the profile of the saturated zone; and
4. Chemical tracer methods.

Based on preliminary review of these methods and their applications, some combination of the first three methods would likely be appropriate for this study purpose. These methods are described briefly below.

Laboratory Soil Column Experiments

Though it has been widely documented that re-compacted column studies (using disturbed soil cores) may not accurately represent field conditions, especially for fine-textured soils, evaluation of intact cores may yield valuable results where field conditions are inadequate to evaluate capillary fringe. Laboratory or bench-scale column experiments have two main advantages. First, they can be conducted any time. Second, the desired conditions (in this case, groundwater depth) can be imposed.

Intact cores are likely a better alternative to packed columns if laboratory studies are pursued. Intact soil cores can be extracted from field sites in acetate sleeves and transported to a laboratory. Acetate sleeves are transparent and allow the observation of moisture profiles in intact soil cores that have been placed in died water, for example. In this case, instrumentation wouldn't necessarily be required to observe capillary fringe.

Care must be taken in combining laboratory and field study results. However, column experiments, particularly if care is taken to use intact cores, may be able to provide relative capillary fringe comparisons between soil types where field studies cannot.

This method would likely be used to evaluate capillary fringe in targeted soil conditions that only exist where groundwater conditions are inappropriate for field observations/measurements.

Portable Instruments that Measure Soil Moisture

Portable instruments have been used successfully to evaluate relative soil moisture but their accuracy and precision are sometimes called into question. They would, however, likely produce good comparisons between sites, although they should be calibrated for each different type of soil. Cal Poly used a portable time-domain reflectometry (TDR) instrument to measure soil moisture content and estimate the extent of capillary fringe, but no saturation percentage was conducted on soil samples. Ideally, to determine the tension saturated zone, and therefore the capillary fringe, the saturation percentage of the soil must be known in addition to moisture content.

Core Sampling for Basic Soil Property Measurements

Basic soil property measurements (such as saturation percentage) conducted on soil cores extracted from the field are generally inexpensive and simple to conduct, and can provide accurate results provided that sampling is adequately representative. This method can be combined with portable instruments mentioned in the previous section, to characterize core moisture conditions and capillary fringe. This approach would likely be the most accurate and the least complicated; however, as in all field methods, desired site conditions must exist at the time of sampling. If other field study efforts, such as those discussed in the almond root zone study plan, were concurrently ongoing, there may also be an opportunity to realize some concurrent efficiencies in selected core locations. A tractor mounted hydraulic probe such as the Geoprobe 6610 DT shown in Figure 3-3 would be well suited to extracting cores from a wide range of sites and depths and would be appropriate for this type of effort.

It is anticipated that this method, in combination with portable instruments mentioned above, would be used to evaluate targeted soil conditions that exist where groundwater depths are suitable to make field observations of capillary fringe.

Chemical Tracers

Tracers are usually chemical compounds injected into the subsurface in order to indirectly estimate flow and storage properties. Tracers are potentially expensive and difficult to work with. They also require appropriate field conditions and testing can be time consuming. In-situ tracer experiments would therefore be limited and may last several days, weeks or even months.

Due to cost and field limitations, chemical tracers are not likely best suited for the purposes of this study.

4.5.2 Site Selection

The criteria for initial site selection should be focused on variables that influence capillary fringe, such as soil texture and groundwater elevation. Other factors related to cultural practices and landowner cooperation are also important. Anticipated site selection criteria are listed below.

- Soil type: This study should include investigations that cover the range of soil types expected in the SJRRP area. Soils can be categorized to best represent the range of conditions using soil survey information and boring logs throughout the study area. This approach would allow the characterization of a range of conditions in the project area and realize efficiencies in time and cost by grouping site conditions.

- Preexisting Salinity or Groundwater Monitoring Data: This criterion would not be a requirement for site selection, however, suitable sites located near previous salinity or groundwater monitoring locations may be preferential for data comparisons and added richness in the study dataset.

- Groundwater Elevation: Orchards located near potentially higher groundwater conditions may be preferred to make field observations of shallower ground water and/or capillary fringe conditions within a targeted depth range (below the effective root zone). Site selection efforts should be aimed to locate a portion, but not all, of selected sites in these areas.

- Spatial Distribution: An effort should be made to distribute preliminary sites across the spatial extent of the SJRRP area in order to represent the range of spatial conditions and assess spatial variability within soil categories.

- Location Relative to Orchards and Irrigation: Unlike the Almond Root Zone Study, study site locations may not need to be within orchards. Representative soil characteristics are most important. These may be independent of crop production since most cultural practices that alter soil characteristics would be above (shallower than) the zone in which testing and observations would be focused. There are also advantages to observing conditions where irrigation is not occurring in order to avoid confusion in sources of soil moisture.

- Site Accessibility/Previous Environmental Clearance: Sites should be located near access roads or farm roads to allow access for field study. In addition, suitable sites near points that had had previous environmental clearance should be given priority in order to reduce the degree of permitting effort that may be required.

5.0 Schedule

The schedule for implementation of Phase 2 study efforts is not yet defined. However, timing would involve the following sequence of tasks, some of which may overlap partially with concurrent efforts.

1. <u>Landowner Coordination and Preliminary Data Collection</u>: This task includes meetings and outreach with landowners. The purpose of this coordination would be to gather input on a Phase 2 study implementation plan and engage participating growers. This effort is under way with intended SCTWG meeting scheduling and would also include compilation of existing field information.

2. <u>Data Review</u>: This task would include data review and data gap analyses (primarily in the case of the capillary fringe study) to guide the refinement of study plans.

3. <u>Core Excavation Pilot</u>: This task would include a pilot trial of core excavation method(s) if intended for Phase 2 study. A small subset of sites would be characterized in preparation for full study implementation to verify feasibility of selected approach(es).

4. <u>Field/Lab Data Collection</u>: This task includes implementation of field and/or bench-scale study efforts and data collection.

5. <u>Data Compilation and Interpretation</u>: This task includes compiling preliminary and field data into appropriate databases and interpretation of those data based on the objectives of the refined study. Interpretations would be focused on developing refined understanding of the characteristics of root zone and/or capillary fringe within the project area per the objectives of the intended studies.

6. <u>Reporting</u>: This task includes documentation of field work and data analysis as well as input from reviewers and involves development of official documentation of study results.

This page intentionally left blank.

Attachment A

Capillary Fringe Literature Review Summary

This page intentionally left blank.

A.1 Purpose

This document summarizes a literature review focused on capillary movement of water in soils as it relates to the thresholds for crop root zone protection in the Seepage Management Plan. The specific objectives of this effort were as follows:

- Define capillary rise and capillary fringe as it is described in scientific literature
- Conduct a scientific literature review and summarize findings on:
  - Influences on and characteristics of capillary fringe;
  - Typical heights of capillary fringes in fine soil types;
  - Spatial and temporal variability of capillary fringe; and
  - Methodologies used to measure capillary fringe in the field – accuracy, convenience, applicability in various soils, etc.
- Identify additional illustrations of capillary fringe used in reference materials and refereed studies to improve understanding among stakeholders
- Determine applicability of existing data to interpretations in current literature
- Recommend potential approaches to refine estimates of capillary fringe specified in current SMP protocols.

A.2 Key Findings

The key findings of the literature review are summarized below. More details on each of these topics are provided in Section 3.

- **The definition of capillary fringe differs among experts.** Some define it as the tension-saturated zone; others define it as a transition zone between the water table and the unsaturated zone, which includes water content that varies from essentially saturated to whatever the content is when it meets water infiltrating from above. *Capillary rise* is defined as the movement of pore water against the flow of gravity.
- **Capillary rise depends on multiple factors.** These include soil type; soil moisture depletion in the root zone; depth to the water table; and recharge.
- **The zone of tension saturation typically referred to as the capillary fringe is discrete or "compact."** This means that soil moisture decreases abruptly above its upper limit.

- **Typical capillary fringe in fine soils varies, but can be large.** Capillary fringe in fine soils is estimated up to several yards in several sources. These estimates of capillary fringe are observed in labs under compacted conditions or modelled, and likely do not represent common field conditions. Estimates of capillary fringe in SMP are low compared to reference sources.

- **Capillary rise varies spatially and temporally.** This is true within relatively short distances (a few feet) and seasons.

- **Capillary rise can be measured in the field. P**ortable soil moisture instruments are available that measure in situ soil moisture, or soil cores can be extracted and measurements made on them. However, soil moisture measurements must be related back to saturation percentage to determine what level of saturation a particular soil moisture in a particular soil represents. Portable instruments that measure soil water content are convenient but precision is questionable, especially in some soil types. Capillary fringe has been measured using the coring technique proposed in the Almond Root Zone Study Plan (Phase 2) and other common soil property measurements.

A.3 Literature Review

The findings of the literature review are presented below in order of the key points presented in Section 2.

A.3.1 Definition of Capillary Fringe

Ronen et al. (2000) note that the definition of the capillary fringe is not uniform in literature. "*It is restricted by some authors to that part of the profile above the water table where water content is equal to the saturated water content value and pressure is negative.*"

In a presentation from the University of Colorado, Boulder, experts state that "*Soil profile can also be described in terms of hydrologic horizons. The ground-water zone (also called the phreatic zone) is saturated. Above the water table is a tension-saturated zone (vadose zone) where the soil is saturated due to capillary rise. Water enters the intermediate zone as infiltration from above (from a precipitation event) and leaves by gravity drainage. Water content may temporarily rise above field capacity. The intermediate zone may extend over many tens of meters (or may be absent in other soil regimes).*"

Alley et al. 1999 describe the water below the subsurface in two principal zones: the unsaturated zone and the saturated zone. Between the unsaturated zone and the water table is a transition zone, the capillary fringe. In this zone, the voids are saturated or almost saturated with water that is held in place by capillary forces. Cloke et al. 2006 define capillary fringe as tension saturated zone. Salem and Hampton 2012 state, "The capillary fringe is the area above the water table occupied by water rising under tension against gravity. The tension-saturated capillary fringe is that part of the capillary fringe which is nearly saturated with a wetting fluid. The wetting fluid rises to partially wet a much larger area." This definition distinguishes between saturated and unsaturated capillary fringe.

Holtzer (2010) described the differences in interpretation of saturated and unsaturated terminology/soil physics. Holtzer submits that the water table is incorrectly defined as "*the atmospheric pressure surface that is coincident with the top of the zone of saturation*". This is incorrect because "*the potential for saturated conditions above the water table in violation of the definition is generally accepted and frequently described in groundwater textbooks*" (and also because non-saturated conditions can exist below the water table). Holtzer (2010) also argues that "*the water table should be defined only as the pressure surface where pore-water pressure is at local atmospheric pressure. Its definition should not refer to saturation. The top of the zone of saturation may be above, at, or below this surface.*" He notes that "*engineers apply the phrase 'unsaturated soil mechanics' to the capillary fringe with full awareness that the capillary fringe is essentially saturated".* To support this claim, he cites two sources: Gillham (1984) and Fredlund (2006).

Summary

The definition of capillary fringe in the literature ranges between the tension saturated zone *only* and the zone that includes a saturated zone but also includes regions of water content lower than saturation. The significance of this is not necessarily to determine which definition is correct, but to clarify which definition is used when capillary fringe is determined in the field. Equally important is to determine which definition of capillary fringe is used when estimates are published in reference materials, studies and field investigations, so that comparisons of capillary fringe may be made correctly.

A.3.2 Characteristics of and Influences on Capillary Rise

Capillary flow depends on soil type, soil moisture depletion in the root zone, depth to the water table, and recharge (Tanji and Keilen, 2002). It is also influenced by timing of irrigation and initial soil content. Capillary flow is a hysteretic process, meaning that it is different when the initial soil moisture is low than when the initial soil moisture is high. Many early formulae to estimate capillary rise did not consider initial soil moisture. While texture is relatively easy to measure, and does not vary in space and time, structure is difficult to quantify and does vary greatly in space and time; hence, it is difficult to estimate and extrapolate capillary rise predictions.

Tanji and Keilen (2002) also state that "*In the presence of high water table, shallow groundwater and its salts may move up into the rootzone (recharge) and down out of the rootzone (discharge) depending on the hydraulic head. Deficit irrigation under high water table may induce rootwater extraction of the shallow groundwater. The salinity level of the shallow groundwater is of some concern under such conditions. However, there does not appear to be a simple conceptual model of capillary rise of water and solutes."*

Ronen et al. 2000 found that the capillary fringe they measured was compact (i.e., there was an abrupt change in soil water content that clearly defined its upper limit). In their study, all soil moisture profiles exhibited an abrupt change in water content at some height above the water table. They also noted that saturated conditions were detected in some regions of the capillary fringe, indicating that the whole region of capillary fringe was not saturated. Over a horizontal distance of 4 m, the height of the capillary fringe varied (Figure A-2). Their data showed that the height of top surface of the capillary fringe changes seasonally, but its shape does not. In other words, the upper limit of the capillary fringe changed in elevation with the seasons, but the “peaks and valleys” were preserved regardless of its elevation.

These results indicate that the capillary fringe, including both saturated and less than saturated regions, including saturated and unsaturated zones, is not accurately represented by a diffuse continuum of soil moisture that decreases gradually as it approaches the soil surface as illustrated in Figure A-1 (used in SMP Appendix H). Rather, the capillary fringe is represented more accurately by the illustration shown in Figure A-2 (Ronen et al. 2000). A simplified version of this understanding of the capillary fringe is corroborated by other sources and presented in Figures A-3 and A-4.

Summary

The height, spatial variation and temporal variation of capillary rise are dependent on several factors. The upper limit of the capillary fringe, even though it may not be saturated by some definitions, is likely better represented by an abrupt change in soil moisture rather than as a point in a diffuse continuum of soil moisture that extends from the water table to the upper limit of the vadose zone.

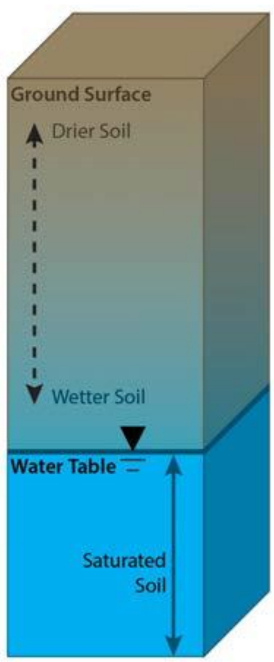

Figure A-1.
(Adapted from Sands 2001)

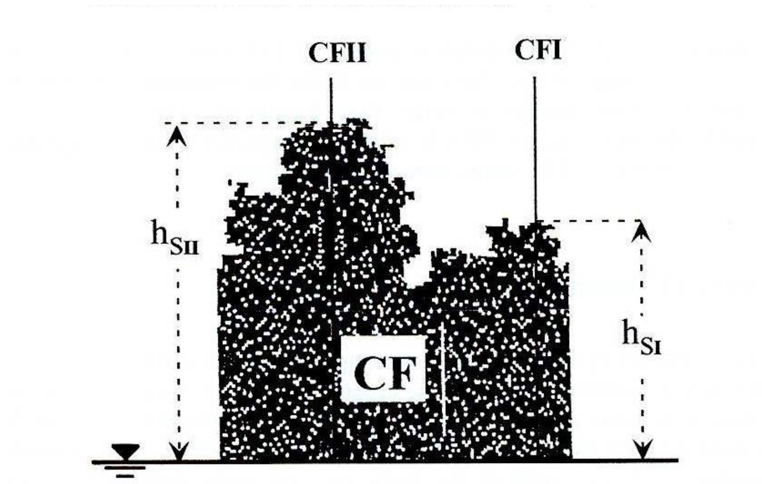

Figure A-2.
Vertical Section of 3D Capillary Fringe Simulation.
CF=Capillary Fringe (I and II); H=Height; S=Saturation.

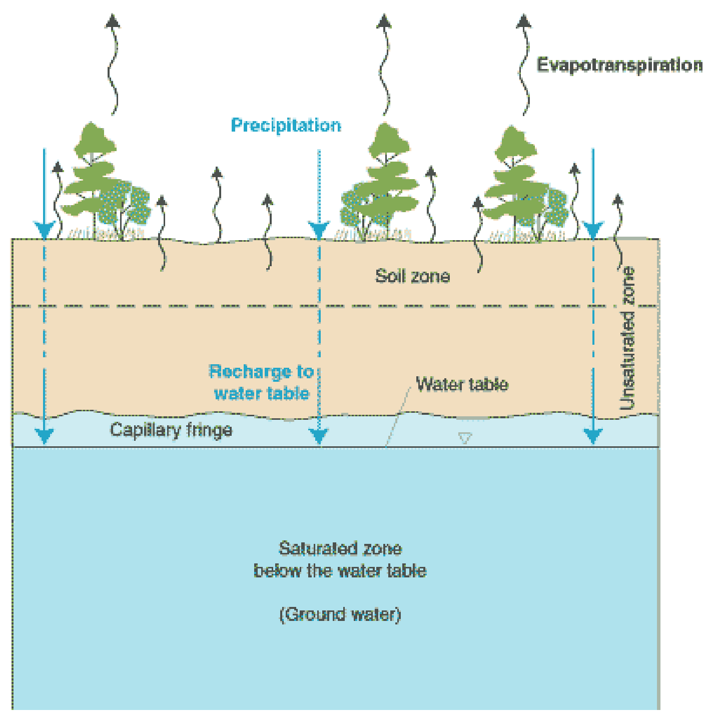

Figure A-3.
The Unsaturated Zone, Capillary Fringe, Water Table, and Saturated Zone.
Alley et al. 1999.

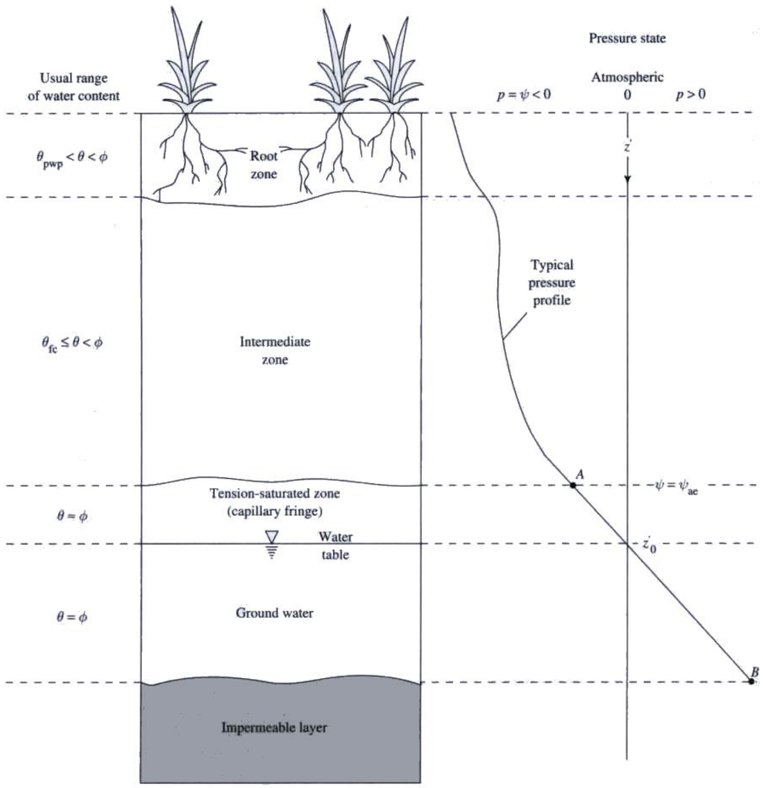

Figure A-4.
Dingman (2002). From University of Colorado Boulder, undated.

A.3.3 Typical Height of Capillary Fringe in Fine Soils

Given the inconsistency in the definition of capillary fringe and the disparity between modelled, laboratory, and field estimates, predictions of capillary rise should be considered with caution. For each estimate of capillary rise, it should be understood whether it is derived from models, formulae, lab tests, or field observations. It should also be understood what definition of capillary rise is being applied, the depth of the water table, what time of year the measurements were taken, etc. In many cases this information is not available. Therefore, the estimates of capillary rise from different sources cannot be meaningfully compared in some cases.

For example, the Roscoe Moss Company in their Handbook of Groundwater Development (1990) includes their definition of capillary fringe in their estimate but does not specify if it refers to materials observed in the field or to laboratory conditions. "*Unbound water continues downward until it reaches the lower boundary of the vadose zone, known as the "capillary fringe". Here pore spaces are completely filled with water. The thickness of the capillary fringe varies from a few inches to several tens of feet, depending upon the nature of materials forming the zone. Material composed primarily of fine particles have a large surface area to volume ratio and may have capillary fringes* *of 50 ft or more."* These estimates may refer to disturbed, lab-derived soil measurements and/or very specific sub-surface conditions.

However, Salem and Hampton (2012) noted the wide range of conflicting data in literature estimating capillary rise in different soils. They submit that the equation that is generally used works reasonably well for coarse-textured soils but greatly over-estimates in fine-textured soils. In fact, they call into question values of 100 cm and above in any soils coarser than a fine sand.

Sumner (1999) provides a table of different soil textures and associated capillary rise, which only extends to several inches (at three to four ft) and therefore is likely referring to agricultural field conditions and not laboratory tests. This source implies that the definition of capillary fringe applied here is only the tension saturated zone.

Burt and Freeman (2010) investigated capillary rise in an agricultural field adjacent to Reach 4A of the San Joaquin River. They measured volumetric soil moisture at 3-inch vertical intervals in 8-ft pit. In this case, the water table was around eight ft. The measurements were taken in October when there was no crop planted and no irrigation. A TDR portable instrument was used that produced results with significant variation. Their results showed that the capillary fringe extended approximately 4.5 feet above the water table. They defined capillary fringe as the saturated zone above the water table, but interpreted the capillary fringe as the depth at which the soil moisture content increased noticeably (rather than determining saturation). They cite Brouwer et al. (1985) for guideline estimates of capillary rise extending up to several meters in fine soils. These estimates, however, are not explained in detail.

Summary

"Typical" heights of capillary fringe published in reference sources should be interpreted with caution if they do not include information that clarifies and defines the estimate. Researchers are investigating new ways of improving calculated predictions of capillary fringe estimates. Calculated, modeled, lab-run and field-observed capillary fringe measurements can vary widely and should not be compared unless they are derived from the same method. Because of the wide range in capillary fringe estimates, site-specific measurements with reliable instrumentation is the best way to determine capillary fringe.

A.3.4 Spatial and Temporal Variability of Capillary Fringe

As described previously, Ronen et al. (2000) found that over a relatively small horizontal distance of 4 m in a medium soil they studied, the height of the capillary fringe varied. This variation, though changing in elevation seasonally, preserved its shape. Cloke et al. (2006) in their study of capillary-fringe "groundwater ridging" investigated the relationship between capillary fringe height, water table response, and hydraulic conductivity in a hillslope-riparian context. Though catchment hydrology is beyond the scope of this effort, it is noted that the authors acknowledged the complicated hydrological systems of riparian zones and their influence on capillary fringe.

Summary

The upper limit of the capillary fringe is spatially and temporally variable. Measurements of capillary fringe should be reported with information indicating time of year, and the spatial resolution at which measurements were made.

A.3.5 Field Methodologies to Measure Capillary Fringe

Field methods of studying capillary fringe range from cumbersome in-situ measurements in actively growing crops over several years (Webster and Topp, 1983) to using micro-injections of deuterium-enriched solution into unsaturated soil (Grönberger et al. 2011). Portable soil moisture instruments have been used as in Burt and Freeman (2010), but the variability of their results is a concern in some soil types. Ronen et al. (2000) used hydraulic probe coring to extract soil samples to 7 m deep. They measured gravimetric water content, bulk density, particle density, saturation percent, pore volume and porosity to determine the extent of saturation throughout the profile. They were able to accomplish 37 cores per day, each about 1.2 m long. This method seems the most practical and feasible, did not require specialized materials or equipment, was time-efficient, did not pose any obvious safety hazards to field staff, and relied on standard soil laboratory tests. Their methods and sample handling were well described and are repeatable.

Summary

Capillary fringe can be measured in the field with standard sampling and analysis methods. Using such a method would likely result in variation of results depending on the spatial resolution of the sampling protocol.

A.4 Recommendations

The field data on soil observations that has already been collected in the project area can be used to develop more refined estimates of capillary fringe. The field data can also be analyzed to determine where there are data gaps, i.e., soils that are underrepresented by existing data. These data gaps can be addressed by incorporating field and/or bench scale investigation of capillary fringe independently or in coordination with almond root zone study field work. With refined assessment of capillary fringe data and the addition of field data, a broader spectrum of capillary fringe estimates can be generated to serve the objectives of the SMP.

A.5 References

Aghajani, H. F., A. S., Piltan, and T. Shourijeh. 2011. An improved solution to capillary rise of water in soils. International Journal of Civil Engineering, Vol. 9, No. 4.

Alley, W.M., T.E. Reilly, and O.L. Franke. 1999. Sustainability of Ground-Water Resources. U.S. Geological Survey Circular 1186. http://pubs.usgs.gov/circ/circ1186/html/gen_facts.html

Brouwer, C., A. Goffeau and M. Heibloem. 1985. Irrigation and Training Manual No. 1. FAO.

Burt, C. and B. Freeman. 2010. Impacts of the San Joaquin River Restoration Flows on Agricultural Fields Adjacent to Reach 4A of the San Joaquin River. ITRC.

Cloke, H.L., M.G. Anderson, J.J. McDonnellc, J.-P. Renaud. H.L. Cloke et al. 2006. Using numerical modelling to evaluate the capillary fringe groundwater ridging hypothesis of streamflow generation. Journal of Hydrology 316 (2006) 141–162.

Grönberger, O., J. L. Michelot, L. Bouchaou, P. Macaigne, Y. Hsissou, and C. Hammecker. Hydrol. 2011. Capillary rise quantifications based on in-situ artificial deuterium peak displacement and laboratory soil characterization. Earth Syst. Sci., 15, 1629–1639, 2011.

Hamed Farshbaf Aghajani, Abbas Soroush, Piltan Tabatabaie Shourijeh. An improved solution to capillary rise of water in soils. October 2010. International Journal of Civil Engineering, Vol. 9, No. 4, December 2011.

Holtzer, T. 2010. Groundwater, Technical Commentary, Vol 48 no. 2 March-April 2010.

Salem and Hampton, 2012. Capillary Rise in Sands and Silts. SSSA Annual Meeting Proceedings. Oct. 23, 2012.

Ronen, D., H. Scher, and M. Blunt. 2000. Field observations of a capillary fringe before and after a rainy season. Journal of Contaminant Hydrology. 44:103-118.

Roscoe Moss Company. 1990. Handbook of Groundwater Development. John Wiley & Sons. 494 pp.

Sumner, M.E. Handbook of Soil Science. 1999. CRC Press. 2048 pp.

Tanji, K.K. and N. C. Keilen. 2002. Agricultural Drainage Water Management in Arid and Semi-arid Areas. FAO Irrigation and Drainage Report 61.

University of Colorado Boulder. Undated. Water in soils: infiltration and redistribution. http://www.colorado.edu/geography/class_homepages/geog_3511_s11/notes/Notes_8.pdf Accessed November 30, 2015.

Webster, D.H. and G.C. Topp. 1983. Measurement of capillary rise under field conditions and related soil properties. Kentville Research Station Technical Bulletin No. 3. Research Branch Agriculture Canada.