Effects of plant uptake and micro-topography on chloride transport in arid soils

Wenming Nie
University of Nevada Las Vegas

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EFFECTS OF PLANT UPTAKE AND MICRO-TOPOGRAPHY ON CHLORIDE TRANSPORT IN ARID SOILS

by

Wenming Nie

Bachelor of Science in Geology
China University of Geosciences, Wuhan, China
2002

Master of Science in Geochemistry
Nanjing University, China
2005

A thesis submitted in partial fulfillment of the requirements for the

Master of Science Degree in Geoscience
Department of Geoscience
College of Sciences

Graduate College
University of Nevada, Las Vegas
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THE GRADUATE COLLEGE

We recommend that the dissertation prepared under our supervision by

Wenming Nie

entitled

Effects of Plant Uptake and Micro-topography on Chloride Transport in Arid Soils

be accepted in partial fulfillment of the requirements for the degree of

Master of Science
Geoscience

Zhongbo Yu, Committee Chair
Michael J. Nicholl, Committee Co-Chair
Michael H. Young, Committee Co-Chair
Wanda J. Taylor, Committee Member
Zhonghai Ding, Graduate Faculty Representative

Ronald Smith, Ph. D., Vice President for Research and Graduate Studies and Dean of the Graduate College

December 2009
ABSTRACT

Effects of Plant Uptake and Micro-topography on Chloride Transport in Arid Soils

by

Wenming Nie

Dr. Zhongbo Yu, Examination Committee Chair
Professor of Hydrogeology
University of Nevada, Las Vegas

Dr. Michael J. Nicholl, Examination Committee Co-Chair
Associate Professor of Geoscience
University of Nevada, Las Vegas

Dr. Michael H. Young, Examination Committee Co-Chair
Associate Professor of Hydrologic Science
Desert Research Institute

Chloride concentration profiles to depths of 1 m were evaluated on a young alluvial fan in Eldorado Valley, NV. It was found that chloride beneath plant canopies were 11 to 222 times higher than adjacent (1 – 2 m away) bare soil locations. Two-dimensional numerical simulations using HYDRUS 2D/3D model were used to further explore the impact of plants on chloride transport. The simulation results indicated that lateral flow driven by root uptake concentrated chloride toward root zones, leading to the accumulation of chloride under plant canopies. Results also suggest that locally micro-topography can have a substantial impact on chloride migration, as runoff into locally low areas (swales) can push chloride deeper into the soil profile than in adjacent high areas (bars). Hence, the uneven distribution of chloride in microsites should be considered when select field sampling sites for paleoflux and age estimates using chloride mass balance method.
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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

The chloride mass balance (CMB) method is a commonly used approach to estimate soil water fluxes and ages (Allison, 1988; Cook et al., 1992; Phillips, 1994; Scanlon et al., 1997). Chloride does not leave the soil with water via evapotranspiration (Walvoord et al., 2002). Thus, the mean recharge rate under steady state can be calculated by dividing the total chloride fallout (from precipitation and dryfall) by chloride concentration in pore water below the vadose zone (Allison, 1988; Cook et al., 1992); and CMB ages can be estimated by dividing the total mass of chloride at given depth by mean annual chloride fallout through precipitation and dryfall (Phillips et al., 1988). One essential assumption in the CMB approach is that chloride only migrates through the vadose zone by one-dimensional downward advection (e.g., Murphy et al., 1996; Scanlon et al., 1997) and being further concentrated at depth from upward flow of water vapor (Walvoord et al., 2002; Yin et al., 2008). However, these simplifying assumptions may lead to non-negligible uncertainties in paleoflux and age estimates, when apparent lateral flow and chloride transport exists in vadose zone soils. Lateral transport of soil water and dissolved constituents is more likely occurred where mosaics of interspersed vegetation and bare soils are recognized as binary systems of canopies versus intercanopies (Caldwell et al., 2008).

Studies have been performed to identify the heterogeneity of hydraulic properties and nutrient distributions from canopy to intercanopy (bare soil) microsites (Schlesinger...
et al., 1996; Cross and Schlesinger 1999; Caldwell et al., 2008). However, it is still unclear whether the spatial heterogeneity of hydraulic parameters and the presence or absence of plant uptake in this binary system will lead to substantial uncertainties in paleoflux and age estimates using the CMB approach. Hence, quantifying chloride distributions beneath plant canopy and nearby intercanopy microsites is necessary. Furthermore, if chloride is unevenly distributed in this binary system, the question can be asked: what are the factors influencing soil moisture and chloride redistributions between canopy and intercanopy microsites? Additionally, if the binary system in arid regions leads to uneven redistribution of chloride, does it also impact the spatial redistribution of nitrate? Recent studies have recognized large amounts of bioavailable nitrogen stored in arid vadose zones (Walvoord et al., 2003), which is a potential source of groundwater contamination. Hence, to better quantify the storage of nitrate in arid soils, we seek to study the spatial distribution and associated transport behavior of nitrate in a binary system of canopy and intercanopy microsites.

1.2 Previous Studies

This section reviews relevant literatures, including studies performed by ecohydrologists in relatively near surface soil layers, and by hydrologists in deeper soil layers.

1.2.1 Studies Focused on Near Surface Soil Layers

Previous studies performed by ecologists and ecohydrologists were mainly focused on shallow soil layers (usually less than 40 cm) to investigate the impacts of desert vegetations on nutrient patterns and hydraulic properties in arid regions.
Schlesinger (1996) and Cross and Schlesinger (1999) examined nutrient patterns in near-surface soils (0-12 cm) in arid grassland and shrubland ecosystems, and reported that nutrient distributions were not significantly influenced by nutrient cycling by grassland, but closely related to the presence of shrubs. They pointed out that N, PO$_4$, Cl, SO$_4$, and K were concentrated beneath shrub canopies, while Rb, Na, Li, Ca, Mg, and Sr were concentrated in intercanopy soils (Schlesinger, 1996; Cross and Schlesinger, 1999). Su et al. (2004) also observed higher concentrations of organic C, total N and P, as well as higher values of electrical conductivity (EC) in surface soils (less than 30-cm depth) under shrub canopies than those in open spaces in northeastern China. In southern Iran, it was also observed that organic matter and chloride accumulated in the canopy soils in the upper 40-cm depth (Sameni and Soleimani, 2007).

Caldwell et al. (2008) investigated the spatial structure of hydraulic parameters of near surface soils (upper 2.5 cm) by representing surface mosaics of canopies and intercanopies as binary systems, and reported lower unsaturated hydraulic conductivities under shrub canopies. Their results indicated that the influence of shrubs on correlations between hydraulic properties, organic matter, and particle size could be extended to about 1.4 times of canopy diameter (Caldwell et al., 2008).

1.2.2 Studies Performed in Deep Vadose Zones

Chloride concentrations in soil pore water collected in deep boreholes served as tracers to indicate soil water movement in semiarid regions (Allison and Hughes, 1983) and to identify spatial variability of unsaturated flow under and adjacent to playas (Scanlon and Goldsmith, 1997). Studies were performed to estimate paleowater fluxes and soil ages using CMB approaches, the results of which were further used to indicate
climate change over the past tens of thousand years ago (i.e., Scanlon, 2000). Steep chloride gradients were observed in near-surface soils (chloride bulge at around 5-m depth, with around 40 cm vertical sampling interval in the upper 10-m depth), indicating wet to dry climate changes at around 10,000 years (Scanlon, 2000). Nitrate-nitrogen (N-NO\textsubscript{3}) profiles were examined in the deserts of western United States, suggesting similar transport mechanisms (Walvoord et al., 2003).

Conceptual and numerical models were also developed to simulate observed chloride profiles in deep vadose zones. Walvoord et al. (2002a) developed one-dimensional models by considering upward flow of water vapor, while simulating liquid water flow and chloride transport in arid vadose zones. The simulated results fitted both soil matric potential and chloride profiles, indicating that the onset of climate change from wet to dry conditions at the Holocene period led to the formation of a chloride bulge (Walvoord et al., 2002a, b). However, simulated results from Yin et al. (2008) (using HYDRUS-1D; Simunek, 2005) indicated that chloride accumulation in vadose zones was triggered not only by climate change, but also by the root uptake of soil water, leaving behind the chloride. Additionally, Yin et al. (2008) showed that chloride accumulated at depths relatively shallower (20-30 cm) than results from other researchers, specifically in the zone of the maximum root zone distribution.

1.2.3 Other Related Studies

As indicated above, the interest of different scientific groups tend to focus on different soil depths and processes: ecologists or ecohydrologists mainly focus on near-surface heterogeneity of nutrient patterns and hydraulic properties, and vadose zone
hydrologists focus more on chloride transport and distribution in deep soils. Hence, very few researchers report chloride patterns in shallow soil profiles that vary from 1 – 1.4 m.

Schlesinger et al. (1989) observed two chloride bulges in the upper 1-m soil under the canopy of *L. Tridentada* in the Mojave Desert, one in the near-surface soil (0 – 10 cm), the other below 75-cm depth. It was later suggested that the trigger for the formation of such bulges was passive water flow, driven by transpiration (Schlesinger and Pilmanis 1998). Marion et al. (2008) reported chloride, nitrate, and other constituents in arid soil (up to 1.4-m depth) beneath canopies and intercanopies at a site in the Nevada Test Site, north of Las Vegas. Here, chloride bulges were observed at around 1-m depth underneath canopies, but N accumulated at deeper depth, suggesting that N accumulation was due to low retention capacity of soil and deep leaching of N. The hydrologic cycling behind the solute redistribution was not considered in this study.

1.3 Objectives and Hypotheses

The objectives of this study are to evaluate the influence of plant uptake on redistribution of solutes in a binary system of canopy and intercanopy microsites, and to investigate the influence of water flux gradients under plant canopies on solute redistribution. More specifically, we will test the following two hypotheses:

1) Chloride and nitrate profiles are associated with the presence or absence of plants, where, the water fluxes beneath plant canopies differ from those of nearby bare soils, which may significantly influence salt redistribution in soil profiles.

2) Plant water uptake and micro-topography may influence water flux under plant canopy, leading to different chloride patterns in soil profiles.
1.4 Investigation Approach

To test these two hypotheses, an integrated study using field, laboratory, and numerical modeling was conducted. The field work was conducted in Eldorado Valley, near Boulder City, Nevada. Soil samples were collected under seven *L. Tridentada* plants and nearby intercanopy microsites. Four plants were located on local topographic highs (bars), and the remaining three plants were located in topographic lows (swales). The soil texture and solute concentrations (chloride, nitrate) were determined in the laboratory. A two-dimensional numerical model was set up to simulate water flow and chloride transport, considering the effects of root water uptake on flow and transport.

1.5 Outline of Thesis

This thesis is divided into chapters that present different aspects of the study. Chapter 2 describes in detail the methods and techniques used for the field investigation and lab analyses. Chapter 3 provides the field and laboratory results. Chapter 4 describes the 2-D conceptual and numerical model and presents the simulation results. Chapter 5 presents the discussion, final conclusions, and future recommendations.
CHAPTER 2

FIELD INVESTIGATION

The primary purpose of this research is to investigate the impacts of plant water uptake and micro-topography on water flow and solute transport in arid soils. Exploring these factors necessitates the identification of a field site where these two effects are not swamped by other factors, including plant size, species, and soil. Thus, desirable field sampling sites for this study will be on young soils with limited structural development and negligible heterogeneity of soil physical properties between the plant canopies and adjacent intercanopy soil zones. To investigate the effects of plant water uptake, soil is sampled directly beneath the canopies of *L. tridentada*, the dominant species in the Mojave Desert, and its adjacent intercanopies. Sampling plants of similar size is preferred to exclude the influence of plant size. To explore the effect of micro-topography (i.e., bar versus swale), investigation should be conducted at sites in close physical proximity that are on locally high or low ground.

This chapter begins with description of the field study site, followed by detailed descriptions of the sampling process and subsequent laboratory measurements on the collected samples.

2.1 Site Selection and Description

The field investigation was performed at on an alluvial fan at the northern end of Eldorado Valley, in southern Nevada. The field site was located at 35°56.15′N, 114°53.93′W, which is approximately 34 km SE of Las Vegas (Figure 2.1, Figure 2.2).
We selected this site for several reasons. First, it fits the desired profile of a desert soil with sparse vegetation. Second, the surficial sediments are relatively young (800 – 1200 years, Doug Merkler, NRCS, personal communication, 2008), thus the effect of soil structure (i.e., horizon development) on water/solute movement was expected to be negligible. Third, the young age also suggests that paleowater flux and solute accumulation is representative of modern climatic conditions, and has not been impacted by the last significantly wetter period (24 to 10 ka) in the western USA (Jannike et al., 1991). The specific location within Eldorado Valley was selected based on the proximity to soil excavation associated with a National Science Foundation Funded investigation entitled: Scaling Environmental Processes in Heterogeneous Arid Soils (SEPHAS). This project was funded as part of SEPHAS, and made use of soil data obtained from that project.

2.1.1 Physiography of Eldorado Valley Field Site

Eldorado Valley extends for about 20 km in the east-west direction and is bounded to the east by Eldorado Mountain and to the west by the McCullough Mountain (DOE, 1996). The valley extents for approximately 80 km in the north-south direction and is bounded to the north by Black Hills and River Mountains and to the south by Highland Range (DOE, 1996). The City of Boulder City is found in the northern part of the valley and the City of Searchlight is found toward the south (DOE, 1996). Elevation ranges from 2152 m (McCullough Mountain) to 521 m (playa in the valley) (DOE, 1994).

Five categories of geologic units were identified (Longwell et al., 1965), including alluvial deposits, older gravels, volcanics, granite, and metamorphics. Alluvial deposits in the valley-floor area are composed of gravel, sand, silt and clay. These
deposits are unconsolidated in most regions, except for the areas close to fault zones and mineralization areas (DOE, 1996). Weakly consolidated old gravels deposited in Late Tertiary to Early Quaternary are presented near the Searchlight area (Figure 2.1, DOE, 1996). Quaternary-, Tertiary-, and Cretaceous-aged, thick volcanic rocks (610 m to 1219 m) have been identified in the NE Eldorado Mountains and northern part of McCullough Range (DOE, 1996). Tertiary- and Precambrian-aged granites (over 1524 m) are located in the central and southern Eldorado Mountains, and probably represent the basement of the valley (DOE, 1996). Precambrian metamorphics (less than 610 m) cross the southern part of the McCullough Range (DOE, 1996).

2.1.2 Climate and Hydrology at Eldorado Valley Field Site

The climate in Eldorado Valley can be represented by the records at Boulder City meteorological station (261071, NOAA, and WRCC) from 1931/10 to 2008/09. The average annual precipitation during 1931/10 to 2008/09 is 13.9 cm. The wettest month is August, when the mean monthly precipitation is 2.16 cm, and June is the driest month with a mean monthly rainfall of 0.27 cm. July is the warmest month with 40 °C mean monthly maximum temperature, and the coolest month is January, when the mean monthly minimum temperature is 0.5 °C.

Eldorado Valley belongs to the Las Vegas Flow System, a subsystem of the Colorado Flow System (DOE, 1996). Surface water supplies in the valley are very limited and mainly from runoff, which is less than $1.0 \times 10^5$ m$^3$/yr (Scott et al., 1971). Groundwater supplies are mainly from recharge over the basin, which is estimated as $1.0 \times 10^6$ m$^3$/yr. Another source of groundwater supply is the inflow from Hidden
Valley, which is less than 370,050 m³/yr (Rush and Huxel, 1966). The groundwater table in Eldorado Valley is 84 to 98 m below the ground surface (Buqo and Giampaoli, 1988).

Groundwater in Eldorado Valley is mainly sodium-bicarbonate type water containing high concentrations of dissolved solids. The salinity hazard is medium to high (Rush and Huxel, 1966). In some areas, concentrations of dissolved solids, sulfate, and chloride are higher than drinking water standards. Groundwater in the Searchlight area is contaminated by iron, lead, manganese, mercury, and nitrate (Buqo and Giampaoli, 1988).

2.1.3 Soils of Eldorado Valley Field Site

The U.S. Bureau of Land Management (BLM, 1992) investigated soils in Eldorado Valley and found them to be very deep, medium-texture saline, and alkaline in the lowland area. Soils on the alluvial fans are gravelly coarse-textured, and soils in mountains are discontinuous, rocky, gravelly and coarse-textured (BLM, 1992). In this study, the field investigation was performed in the alluvial fan areas.

A 3-m deep trench (borrow pit) was opened in Eldorado Valley on December, 2007 to obtain 100 cubic meters of soil for use in the SEPHAS project. The surface age in the borrow pit was visually estimated as ranging between 800 and 1200 years (Doug Merkler, NRCS, personal communication, 2008). Soils in the borrow pit were characterized by sandy texture and poorly developed (single grained) structure with very little cohesion (Young et al., 2007). Four soil deposits in the upper 3-m depth were visually identified by texture, cohesiveness, and color. The thicknesses of the upper four layers were measured at 30, 70, 100 and 100 cm (Young et al., 2007). Soil texture of the four soil layers is: layer 1, fine/medium sand with some clasts; layer 2, fine sand with
more gravel and silt; layer 3, gravel/cobble lenses in sand; and layer 4, stage 2 petrocalcic (Young et al., 2007).

2.1.4 Plant Communities of Eldorado Valley Field Site

Eldorado Valley is located in the southern Mojave Desert, where the plant communities are composed of evergreen shrubs, drought-deciduous shrubs, perennial forbs and grasses, succulents, and winter annuals (Young et al., 2006). Similar to other locations in southern Mojave Desert, the dominant plant species in Eldorado Valley are creosotebush (*Larrea tridentada*) and white bursage (*Ambrosia dumosa*). As shown in Figure 2.3, the average size of *Larrea tridentada* is much larger than the *Ambrosia dumosa*. The rooting depth for these two species is about 100 cm. The root density increases to the maximum at around 60-cm depth and then generally decreases exponentially given the limitation of water resources, leading to more than 90% of root mass distributed in the top 100 cm soils in arid regions (Jackson et al., 1996; Kemp et al., 1997). Canopy diameters, plant intervals, and occupied areas for these two dominant species were measured at our field site in May 2008. Measured canopy diameters of *L. tridentada* ranged from 0.6 to 2.1 m, and between 0.2 and 0.9 m. for *A. dumosa*. Average canopy diameters of these two species are 1.21 m and 0.46 m, respectively, and average occupied areas of *L. tridentada* and *A. dumosa* are 13.5 m² and 3.13 m². The average distance between *L. tridentada* plants is about 4 m; and around 2 m between *A. dumosa* shrubs. In this study, the field soil sampling was performed under the large-size dominant species, *L. tridentada*, and its adjacent bare soil zones.

The *L. tridentada* prefer to occupy well-drained soils associated with *A. dumosa*. *L. tridentada* is a long-lived species of plant; as an example, an 11,700-yr old shrub was
identified by Vasek (1980). In high temperature conditions, mature plants are more tolerant to drought stress than the young shrubs, and can survive under conditions with soil water potentials as low as -80 bars (Odening et al., 1974).

2.1.5 Human Influence in Eldorado Valley Field Site

The field survey site is located east of Route 95, about 4 km south of the intersection of routes 93 and 95. The land in Eldorado Valley is used for grazing, light industry, and recreation. Several light industries are found in the NW portion of the basin area, and recreation activities are found in the playa areas, SW of the field site. Our field investigation was conducted upslope of the playa region, where power lines and roads are regularly situated.

2.1.6 Micro-Sites Selected for Sampling

The field sampling site location was chosen to be away from disturbed zones (roads, structures, excavation, etc.) and outside of obvious recently active channels. The relative positions of the sampling sites are shown in Figure 2.4. Four sampling sites are on locally high areas (bars, B1-B4), and three sites in low ground areas (swales, S1-S3). It is expected that some precipitation falling in the bar areas will flow into the adjacent swale region through surface runoff, hence increasing the effective precipitation in the swales with respect to the bars. We collected soil samples in the bar and swale regions to investigate effects of micro-topography on paleowater flux and solute redistribution.

2.2 Sample Collection

Field sampling was performed on two occasions. A scoping investigation was performed in May 2008 and the bulk of the sampling was performed in February 2009.
2.2.1 Scoping Investigation

A mature, healthy *L. Tridentada* plant on a bar (labeled as B1 on Figure 2.4) with a branch diameter of 1.40 m was selected for sampling. The interval between the center of the canopy and the center of the adjacent intercanopy microsite was 2.35 m. Individual pits were opened by hand under the selected plant and the adjacent intercanopy. Soil samples were gathered along the edge of each pit, with eight vertical profiles selected four from each pit. Detailed sampling protocols are described below. One profile was chosen under the canopy, in the center of plant (B1C), with two other profiles chosen on one side of the plant, and one chosen on the opposite side. Intervals between these four profiles were 40 cm. Similar to the canopy pit, one vertical profile was situated in the center of intercanopy (B1I) with two locations chosen on one side of the interspace, and one chosen on the opposite side. Profile intervals were also 40 cm. We collected 10 samples at 10-cm interval in depth from each profile. Samples from profiles B1C and B1I were selected for analysis of particle size distribution and chemical species concentrations.

2.2.2 Main Sampling Event

After evaluating data collected in the scoping investigation, the site was revisited in February 2009. At that time, six mature and healthy *L. Tridentada* plants with adjacent intercanopy sites were selected for further sampling. Three plants were located on bar areas (B2-B4), three others in swale areas (S1-S3). From Figure 2.4, it can be seen that the selected plants, as well as plant B1, which was selected in the scoping investigation, were almost along a NW-SE line to exclude the effects of topographic aspect on water flow or salt redistribution. A temporary reference monument was established at ground
level, 5 m north to the edge of SEPHAS borrow pit. A hand level, compass, and stadia rod were used to measure the relative direction, distance, and elevation of seven canopy locations that were studied. The temporary reference monument was located at 35°56.15′N, 114°53.93′W, with 560 m elevation; the hand level was set an elevation of 1.7 m. The measurements are shown in Table 2.1.

Twelve trenches were opened by hand at the selected microsites, each for plant canopy and intercanopy. Sampling was destructive in that trenches bisected each plant to allow sampling directly beneath the plant. Under canopy samples were taken within 20 cm of the stem of the shrub. After Caldwell et al. (2008), we collected intercanopy samples at a distance of at least 1.4 times of the canopy diameter, to ensure that we were outside of the influence of the shrub. It is important to notice that the ability to meet this criterion is wholly dependent on the spatial distribution of the vegetation. To select creosote shrubs following a NW-SE distribution crossing bars and swales, we were unable to uniformly meet the criterion suggested by Caldwell et al. (2008). In our field survey, ratio of microsite interval over canopy diameter ranged from 0.93 to 1.70 (Table 2.2). Samples were collected over 10-cm intervals in depth from ground surface down to 100 or 110 cm.

2.2.3 Sampling Protocols

In the scoping investigation, samples were collected along side walls of eight selected profiles in the opened pits under canopy B1 and the adjacent intercanopy. In the main investigation, samples were gathered from the side wall of 12 trenches opened at selected microsites. The sampling processes are the same for the two field investigations. At each vertical profile or trench, a 10-cm deep block (e.g., 0 to 10 cm depth) was
removed using a sampler. Looseness of the soils led to mixed samples rather than intact. This process was repeated for each interval to the bottom of the trench, at a depth of 100 or 110 cm.

In the scoping investigation, profiles under the shrub canopy were labeled as PA, PL, PC, PR from west to east, and profiles under the adjacent canopy were labeled as ID, IC, IA, IB from west to east. Samples collected from each profile were labeled as the depth to the ground surface. As an example, PC30-40 was the sample collected at 30 to 40 cm deep beneath surface at profile PC.

In the main investigation event, we labeled sampling sites as B2 to B4 (Bar), and S1 to S3 (Swale) from northwest to southeast. The under canopy soil profiles were labeled as C, and profiles in intercanopy areas were labeled as I. Samples collected from each profile were labeled as 1 to 10 or 11 from surface to 100 or 110 cm depth. For example, B3C5 referred to the sample collected under shrub canopy B3 at 40-50 cm deep and B3I10 was the sample gathered from nearby intercanopy of B3 shrub at the depth of 90-100 cm. To be consistent with the main investigation, samples taken from profiles PC and IA were labeled as B1C and B1I, and the depth labeled at the scoping investigation were changed into 1 to 10 as we did in the main investigation survey. As an example, samples PC 0-10, IA30-40 were relabeled as B1C1, B1I4, respectively.

In the scoping survey, samples were stored in labeled zip-lock plastic bags. Only samples in profiles PC and IA (B1C and B1I) were selected to analyze the particle size distribution and chemical species concentrations. In the main survey event, each collected sample was separated into two portions. The portion prepared for Nitrate-N analysis was placed into labeled zip-lock plastic bags after sieving through No. 10 sieve (2-mm mesh).
and stored in a cooler with dry-ice to prevent denitrification (personal communication with Dr. Yuanxin Teng, Environmental Soil Analysis Lab at UNLV, 2009). The denitrification usually occurs when soil sample is wet (personally communication with Dr. Jarai Mon in DRI, Las Vegas, 2009). Another portion of the sample was used for chloride and particle size analyses. These second sieved samples were stored in labeled zip-lock plastic bags.

2.3 Soil Analysis

2.3.1 Particle Size Distribution Analysis

We analyzed particle size distribution for 121 soil samples collected in the main investigation survey following the wet sieving method used at the Quaternary Soil Analysis Laboratory at the Desert Research Institute in Reno, Nevada (DRI, 2005). Measurements followed the procedure described below.

1) **Determine gravel percentage:** A representative sample was exposed to the atmospheric condition for over 48 hours in a low (15 to 30%) humidity condition. Next, the air dry sample was sieved using a #10 screen (2-mm openings). The material passing the #10 sieve was measured to 0.01-g resolution \( M_{\text{pass#10}} \). Material retained on the screen was washed, dried, and weighed to the nearest 0.01 g to get the mass of gravel \( M_{\text{gravel}} \).

2) **Measure air dry soil moisture:** A subset (around 30 g) of \( M_{\text{pass#10}} \) was weighed to the nearest 0.01 g \( (M_{\text{air dry}}) \) then oven dried and reweighed \( (M_{\text{oven dry}}) \) to get the air dry moisture content.
3) **Wet sieving to separate sand from silt-clay fraction:** The air-dried soil was pulverized with a mortar and pestle to break up clasts. Then, ~40 g of the pulverized soil was passed through a #10 sieve \((M_1)\) into a 200 mL container. Next, 100 mL of hexametaphosphate solution (~40g/L) was added. The mixture was stirred until the soil was thoroughly wetted, then allowed to soak for at least 16 hours. The dispersed sample was wet sieved through a #230 mesh (63 µm) sieve with deionized water until the water ran clear.

4) **Dry sieving to remove any residue of silt-clay fraction:** The sand retained on sieve in step 3 (above) was washed into an aluminum weighing dish, then placed in an oven set at 105° C for at least 24 hours or until it dried. After drying, samples were cooled in a dessicator and weighed to the nearest 0.01g \((M_2)\). The dried sample was then transferred to a #230 sieve with pan and lid. The sieve was placed on a Gilson sieve shaker for around 10 minutes with vibration setting at 5 and electric tapping function on. The sieve was cleaned by manual brushing after each use. The final step was to weigh the material passing through the #230 sieve to the nearest 0.01g \((M_3)\).

After completing the above process, the moisture, percentages of gravel, sand, and fines (silt plus clay) were calculated using the following relationships:

\[
\text{Moisture} = \frac{M_{\text{airdry}} - M_{\text{ovendry}}}{M_{\text{airdry}}}
\]

\[
\%\text{Gravel} = \frac{M_{\text{gravel}}}{M_{\text{gravel}} + M_{\text{pass #10}}(1 - \text{Moisture})}
\]

\[
\%(\text{Silt + Clay})_{\text{Fraction}} = \frac{M_1(1 - \text{Moisture}) - M_2 + M_3}{M_1(1 - \text{Moisture})}
\]

\[
\%\text{Sand}_{\text{Fraction}} = 1 - \%(\text{Silt + Clay})_{\text{Fraction}}
\]
e) \[ \%\text{Sand} = (1 - \%\text{Gravel}) \times \%\text{Sand}_{\text{Fraction}} \]

f) \[ \%(\text{Silt + Clay}) = (1 - \%\text{Gravel}) \times \%(\text{Silt + Clay})_{\text{Fraction}} \]

We conducted particle size distribution analysis for 20 samples at profiles B1C and B1I by following ASTM procedure (2002, D 421-85 and D422-63). The ASTM procedure (ASTM, 2002) only includes the first three steps from the above process, which could lead to an underestimation of the silt-clay fraction. Additionally, the air dry soil (gravel included) prepared for analysis in ASTM procedure is around 200 g, instead of using around 40 g of air-dried soil pulverized to pass #10 in steps 3 of the above process.

2.3.2 Chemical Analysis

A total of 20 samples collected during the scoping event were sent to A & L Western Agricultural Laboratories to be analyzed for: potassium, magnesium, calcium, sodium, sulfate-S, pH, cation exchange capacity (CEC), and soluble salts. Then, for the second sampling event, we evaluated all samples for soil nitrate and chloride concentrations. In addition, samples at profiles B1C and B1I collected in the scoping investigation were also analyzed for soil chloride concentration. Considering the influence of denitrification, we did not analyze these samples for soil nitrate concentration.

We measured soil nitrate concentration on 122 samples and chloride concentration on 142 samples. An ion exchange method was used for nitrate extraction. Here, 10 g of the <2-mm fraction of each soil sample was mixed with ~50 g of 0.01 M/L of CaCl₂ solution for a 1/5 soil-water ratio (Mulvaney, 1996). The mixture was shaken for 24 hours on a Platform Shaker set at 255 rpm. Extracts were centrifuged for 15
minutes in Eppendorf ® Centrifuge 5810R at 4000 rpm (3220 g) and filtered. Nitrate concentrations of the extractions were determined using a 9707 BNWP ionplus ® Nitrate Combination Electrode in the Soils Laboratory at the Desert Research Institute in Las Vegas, Nevada. The recommended concentration range for the nitrate electrode is 0.1 to 14,000 ppm nitrate-nitrogen, and the error is ±2% for direct electrode measurements with hourly calibration.

Chloride was extracted from the < 2-mm fraction at a 1/5 soil to water ratio (Rhoades, 1982). For each sample, ~ 8 g of the < 2-mm fraction was placed in a centrifuge tube with ~ 40 g of distilled water (18.2 MΩ), then shaken for 5 hours on a Platform Shaker at 255 rpm. Extracts were centrifuged for 15 minutes in Centrifuge 5810 R with 4000 rpm (3220 g) and filtered by hand. Extractions were sent to the Environmental Soil Analysis Lab at UNLV to determine Cl⁻ concentrations (Dionex ICS 3000 with recommend determine range > 0.05ppm).
Table 2.1 Relative position of sampling sites to the reference frame.

<table>
<thead>
<tr>
<th>Site</th>
<th>Direction</th>
<th>Height (m)</th>
<th>Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-1</td>
<td>343°</td>
<td>0.0</td>
<td>29.8</td>
</tr>
<tr>
<td>B-1</td>
<td>20°</td>
<td>0.2</td>
<td>22.2</td>
</tr>
<tr>
<td>B-2</td>
<td>39°</td>
<td>0.4</td>
<td>23.8</td>
</tr>
<tr>
<td>S-2</td>
<td>60°</td>
<td>0.1</td>
<td>28.7</td>
</tr>
<tr>
<td>S-3</td>
<td>65°</td>
<td>0.0</td>
<td>25.9</td>
</tr>
<tr>
<td>B-3</td>
<td>72°</td>
<td>0.4</td>
<td>40.1</td>
</tr>
<tr>
<td>B-4</td>
<td>80°</td>
<td>0.5</td>
<td>45.4</td>
</tr>
</tbody>
</table>

Table 2.2 Relative position of canopy to intercanopy at each microsite.

<table>
<thead>
<tr>
<th>Site</th>
<th>Direction</th>
<th>Distance (D) cm</th>
<th>Plant Size (PS) cm</th>
<th>Ratio D/PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-1</td>
<td>155°</td>
<td>238</td>
<td>140</td>
<td>1.70</td>
</tr>
<tr>
<td>B-1</td>
<td>285°</td>
<td>235</td>
<td>140</td>
<td>1.68</td>
</tr>
<tr>
<td>B-2</td>
<td>79°</td>
<td>170</td>
<td>120</td>
<td>1.42</td>
</tr>
<tr>
<td>S-2</td>
<td>304°</td>
<td>160</td>
<td>145</td>
<td>1.10</td>
</tr>
<tr>
<td>S-3</td>
<td>192°</td>
<td>145</td>
<td>140</td>
<td>1.04</td>
</tr>
<tr>
<td>B-3</td>
<td>98°</td>
<td>190</td>
<td>160</td>
<td>1.19</td>
</tr>
<tr>
<td>B-4</td>
<td>130°</td>
<td>185</td>
<td>200</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Figure 2.1 Eldorado Valley and surrounding area.

Red box shows the field investigation area (From DOE, 1996)
Figure 2.2 Satellite image shows the location of field site.

(After Young et al., 2007)

Figure 2.3 Ecologic patterns in Eldorado Valley, NV.
Figure 2.4 Relative positions of field sampling sites to the reference frame.

Numbers in brackets are relative height to the reference frame in meters.
CHAPTER 3

RESULTS OF THE FIELD INVESTIGATION

Field observations of soil texture and laboratory analyses of the soil chemistry along the excavation walls are reported in the following sections. Observations of soil structure and texture are presented first, and then the broad spectrum chemical analysis measured at site B1. Analyses of Cl- for all sites are presented next, followed by an analysis of NO₃-N for all sites except B1, where NO₃-N was not measured.

3.1 Soil Structure

The estimated soil surface age on the alluvial fan that was sampled is between 800 to 1200 years (Doug Merkler, NRCS, personal communication, 2008). Soils show little development and are well drained. Soil structure under plant canopies is similar to those observed at adjacent bare soils and between the swales and bars.

The general soil structure at the field site is shown in Figure 3.1, and was observed to be massive, or single grained. Some layers were visually observed, however, with distinct horizons from 0-50 cm, 50-90 cm, and from 90 cm to the bottom of the trench, where gravel content was higher (Figure 3.1). No caliche layer was observed in the top 100 cm of soil.

3.2 Soil Texture

Vertical distribution patterns for gravel content, which is calculated as 

\[
\frac{M_{\text{Gravel}}}{M_{\text{Gravel}} + M_{\text{Sand}} + M_{\text{Silt+Clay}}} \times 100\%
\]

are shown in Figures 3.2 and 3.3. Gravel profiles
are similar at individual sites, except at sites S2 and S3 (Figure 3.2), where gravels are uniformly distributed with depth in intercanopy sites but with a gravel bulge at depth under canopies.

The gravel profiles beneath canopy and intercanopy sites were shown in Figure 3.3. Under the plant canopies, gravel patterns are similar between bars and swales, with generally lower contents (5.7-14.0%) in near surface layers (around 5-35 cm), except site S1 (53.8-55.7%). In the intercanopy sites, however, the overall gravel contents are lower in the bar areas than in the swale areas. In particular, a relatively lower gravel contents is found in near surface horizons (6.2-22.3% at 5-35 cm) in the bar areas.

Soils at the upper 100 or 110 cm at the seven field sites are classified as sand or loamy sand based on soil definition of USDA (1993), both under canopies and intercanopies. Overall, the fine-textured fractions \( \left( \frac{M_{\text{Silt+Clay}}}{M_{\text{Sand}} + M_{\text{Silt+Clay}}} \times 100\% \right) \) range from 1.6% to 14.7% in soils under plant canopies and from 1.1% to 13.9% in intercanopy sites (Figures 3.4 and 3.5). At each individual site, the vertical profile of the fine fraction is similar between the canopy and adjacent intercanopy (Figure 3.4). Overall, the fine fraction shows only small variability with depth, except that some sites show increased fines in the topmost layers. When viewed as a group (Figure 3.5), no clear differences were seen in fine fraction either between canopy and intercanopy or between bar and swale. The fine fractions at site B1 are relatively smaller relative to other sites. However, the lower contents of fine texture at site B1 are likely due to the different analysis procedure applied to these samples as discussed in chapter 2, rather than due to the spatial heterogeneity of soil texture at the investigation site.
3.3 Chemical Profiles at Site B1

As shown in Figure 3.6, vertical patterns of soil chemical profiles at site B1 differ between the plant canopy and adjacent intercanopy microsites. The overall values of measured parameters, including soluble salts, Cation Exchange Capacity (CEC), concentrations of Mg$^{2+}$, Ca$^{2+}$, SO$_4^{2-}$, Na$^+$, K$^+$, and Cl$^-$, are higher in soils beneath the plant canopy than those in soils in the intercanopy microsite. As shown in Table 3.1, the ratio of average values in the upper 100 cm of the soil profile under the plant canopy over that of intercanopy ranges from 1.3 for Ca$^{2+}$ and CEC to 149.4 for Cl$^-$. Except for K$^+$, each measured parameter shows similar values between plant canopy at depths from 0 to about 40 cm; below 40 cm, values are higher under the plant canopy, with most values reaching a maximum at depths of 70-80 cm. Conversely, these same parameters remain relatively constant with depth in the intercanopy microsite. The K$^+$ concentration behaves in an opposite manner, as concentration under the plant canopy is relatively higher in near surface horizons, and then decrease with depth to match the intercanopy values. The K$^+$ concentration also differs from the other measured parameters in that it is the only one showing a significant “bulge” in the intercanopy area.

To illustrate the differences between microsites, Figure 3.7 shows the ratio of chemical measurement between canopies and intercanopies (C/I) for each parameter at Site B1. Values of C/I greater than 1 suggest that the plant is concentrating the measured parameter, while C/I equal to 1 indicates no effect. With minor or localized exceptions, all measured parameters show C/I > 1, suggesting significant concentration in the canopy profile. Of the chemical species, Ca$^+$ shows the lowest concentration, while Cl$^-$ is concentrated by factors ranging from about 2 to 10,000 in depth. The relatively low
concentration factors for CEC (0.8 – 1.3) and for soluble salts (1.3 – 18.5) suggest that those factors are controlled by less mobile cations than the more mobile Cl⁻.

The vertical distributions of the chemical concentration ratio of canopy soils over bare soils at site B1 are similar to vertical patterns of corresponding chemical concentrations under the canopy (Figures 3.6 and 3.7). For K⁺, the ratio is relatively higher in near surface layers, and then they decrease with depth. For other species, the ratio increases with depth, and a “bulge” exists at depth from 55 to 95 cm.

3.4 Chloride Concentration Profiles for All Sites

The data obtained in this study shows substantial differences in the chloride profiles between canopy and intercanopy microsites. At all of the measured sites, chloride concentrations are higher in soil beneath canopy sites than at the intercanopy microsites (Figure 3.8). The degree of chloride enhancement varies between the sites but is evident at all of them. At the intercanopy sites, chloride values are small (0.01 to 5.07 mg/kg.soil) and remain nearly uniform with depth (Figure 3.9). Under the plant canopies, chloride bulges at site B4 and S1 (27.27 and 18.70 mg/kg.soil respectively) are much smaller relative to the rest of sampling sites (47.79 to greater than 293.94 mg/kg.soil). At the bar areas, chloride is concentrated under plant canopies at depths between 55 and 105 cm (Figure 3.9). Two small bulges are present under plant B4 at depths of 55 cm and 95 cm, respectively. Under plant canopies in the swale areas, the trend of soil chloride concentrations suggests that the bulges are probably deeper than 95 cm, except for concentrations observed at S1 (Figure 3.9).
The ratio of chloride concentration at the canopy to intercanopy sites (C/I) exceeds 1 in all cases (Figure 3.10) illustrating that the presence of a plant consistently enhances the chloride concentration at the microsite. Overall, the C/I ratios range from 4.0 to 11151.9 in relatively deeper soils (55 to 95 cm) and from 1.1 to 112.2 in near-surface soils (5 to 45 cm). As shown in Table 3.2, the average C/I range from 8.3 at site S1 to 260.2 at site S2.

3.5 NO3-N Profiles for Sites B2-B4 and S1-S3

The nitrate-nitrogen (NO$_3$-N) profiles follow similar vertical patterns as those observed for chloride. NO$_3$-N bulges (19.32 to 61.13 mg/kg.soil) are also observed under plant canopies at depths between 45 and 55 cm (Figures 3.11 and 3.12) at both bar and swale areas. The bulge depth of NO$_3$-N differs from that of chloride, which was observed to occur from depths of 55 cm to more than 100 cm and varied between swales and bars. Similar to chloride, two NO$_3$-N bulges are noted at site B4 and bulges observed at B4 or S1 are smaller than observed at the rest of the field sites (Figures 3.11 and 3.12). By comparison, NO$_3$-N is uniformly distributed in the vertical direction at the intercanopy microsites, ranging from 10.93 to 17.67 mg/kg.soil Small NO$_3$-N bulges are noted in the intercanopies at 45-55 cm deep (14.58 to 17.62 mg/kg.soil), but they may not be significant.

The ratio of NO$_3$-N at the canopy to intercanopy (C/I) is shown as Figure 3.13. The vertical patterns of soil NO$_3$-N ratio are similar to NO$_3$-N profiles under the canopies. Ratios are relatively lower in near surface layers (5 to 45 cm) and “bulges” exist at depth between 45 and 85 cm. The ratios of average NO$_3$-N in the top 100 cm
range from 1.3 at site S1 to 2.1 at site S3 (Table 3.3). The ratios of NO$_3$-N at C/I are much lower than those of chloride (Figures 3.10 and 3.13), suggesting that the accumulation of these two species under canopies are controlled by different factors.

3.6 Correlation between Cl- and NO3-N

Overall, the NO$_3$-N concentrations are positively correlated with chloride contents ($R^2=0.54$) when values are plotted in natural logarithmic scales (Figure 3.14). However, the correlations between chloride and nitrate decrease when evaluated separately in canopy or intercanopy microsites, with 0.27 and 0.18 $R^2$ values, respectively (Figure 3.14).
Table 3.1 The ratio of average chemical contents under canopy over intercanopy at site B1.

<table>
<thead>
<tr>
<th>Site</th>
<th>Soluble Salts</th>
<th>Mg</th>
<th>Ca</th>
<th>CEC</th>
<th>SO4</th>
<th>Na</th>
<th>Cl</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercanopy</td>
<td>0.2</td>
<td>125.5</td>
<td>2627.4</td>
<td>14.9</td>
<td>17.0</td>
<td>26.7</td>
<td>0.6</td>
<td>241.6</td>
</tr>
<tr>
<td>Canopy</td>
<td>2.0</td>
<td>191.5</td>
<td>3372.2</td>
<td>19.8</td>
<td>469.7</td>
<td>123.4</td>
<td>84.8</td>
<td>350.4</td>
</tr>
<tr>
<td>Ratio</td>
<td>8.3</td>
<td>1.5</td>
<td>1.3</td>
<td>1.3</td>
<td>27.6</td>
<td>4.6</td>
<td>149.4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 3.2 The ratio of average chloride contents under canopy over intercanopy.

<table>
<thead>
<tr>
<th>Sites</th>
<th>S1</th>
<th>B1</th>
<th>B2</th>
<th>S2</th>
<th>S3</th>
<th>B3</th>
<th>B4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercanopy</td>
<td>0.9</td>
<td>0.6</td>
<td>2.1</td>
<td>0.3</td>
<td>0.8</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Canopy</td>
<td>7.7</td>
<td>84.8</td>
<td>96.8</td>
<td>86.5</td>
<td>18.5</td>
<td>26.3</td>
<td>6.4</td>
</tr>
<tr>
<td>Ratio</td>
<td>8.3</td>
<td>149.4</td>
<td>47.2</td>
<td>260.2</td>
<td>22.8</td>
<td>63.9</td>
<td>13.4</td>
</tr>
</tbody>
</table>

Table 3.3 The ratio of average NO$_3$-N contents under canopy over intercanopy.

<table>
<thead>
<tr>
<th>Sites</th>
<th>S1</th>
<th>B2</th>
<th>S2</th>
<th>S3</th>
<th>B3</th>
<th>B4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercanopy</td>
<td>12.9</td>
<td>14.9</td>
<td>13.9</td>
<td>14.0</td>
<td>15.1</td>
<td>13.0</td>
</tr>
<tr>
<td>Canopy</td>
<td>16.2</td>
<td>27.7</td>
<td>20.2</td>
<td>29.5</td>
<td>30.9</td>
<td>22.6</td>
</tr>
<tr>
<td>Ratio</td>
<td>1.3</td>
<td>1.9</td>
<td>1.5</td>
<td>2.1</td>
<td>2.0</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Figure 3.1 General soil layering structure at the field sampling site.
Figure 3.2 Vertical patterns of gravel content at seven individual sampling sites.

\[
\frac{M_{\text{Gravel}}}{M_{\text{Gravel}} + M_{\text{Sand}} + M_{\text{Silt-Clay}}} \times 100\%
\]

(Gravel content: \[M_{\text{Gravel}}\] + \[M_{\text{Sand}}\] + \[M_{\text{Silt-Clay}}\])
Figure 3.3 Vertical distributions of gravel content at canopy and intercanopy microsites.

Gravel content:

\[ \frac{M_{\text{Gravel}}}{M_{\text{Gravel}} + M_{\text{Sand}} + M_{\text{Silt+Clay}}} \times 100\% \]
Figure 3.4 Vertical patterns of fine texture fraction at seven individual sampling sites.

\[
\text{Fine texture fraction: } \frac{M_{\text{Silt+Clay}}}{M_{\text{Sand}} + M_{\text{Silt+Clay}}} \times 100\%
\]
Figure 3.5 Vertical distributions of fine fraction at canopy and intercanopy microsites.

Fine texture fraction: \[
\frac{M_{\text{Silt+Clay}}}{M_{\text{Sand}} + M_{\text{Silt+Clay}}} \times 100\%
\]
Figure 3.6 Vertical distributions of chemical species at site B1.
Figure 3.7 Vertical distributions of chemical content ratio of canopy over intercanopy at site B1.
Figure 3.8 Vertical patterns of soil chloride concentrations at field sampling sites.
Figure 3.9 Vertical distributions of chloride contents at canopy and intercanopy microsites.
Figure 3.10 Vertical distributions of soil chloride content ratio of canopy over intercanopy.
Figure 3.11 Vertical patterns of NO$_3$-N at seven individual sampling sites.

Solid line: canopy profile, dash line: intercanopy profile.
Figure 3.12 Vertical distributions of NO$_3$-N contents at canopy and intercanopy microsites.
Figure 3.13 Vertical distributions of soil NO3-N ratio of canopy over intercanopy.
Figure 3.14 Diagram shows correlation between Ln(Cl-) and Ln(NO$_3$-N).
CHAPTER 4

SIMULATING EFFECTS OF ROOT UPTAKE ON CHLORIDE TRANSPORT

The major objectives of the conceptual and numerical models are to explore the impact of plant water uptake and micro-topography on paleowater fluxes in arid soils. The transport of conservative chloride, a commonly used index of paleowater flux, is included in the simulation. Without determined ages of surface soils and plants, the model results will not be fitted the specific chloride profiles measured in Eldorado Valley, but instead they will be used to examine the chloride patterns more generally. To explore the impact of lateral water flow on chloride redistribution, the numerical model is set up as a two dimensional vertical plane with the presence of plant root zones and adjacent intercanopy (bare) soils. We assume that detailed knowledge of the soil properties is not needed in the model but instead can be represented by materials consistent with the in situ soils. More specifically, the simplified model is used to explore the effects of wet versus dry climates, plants versus no plants, microtopography (bar versus swale), inclusions of heat transport, and compressed precipitation.

4.1 Physical Model Description

The vertical extent of the model domain was set to 4 m, based on observations of no significant changes of soil water potential below the depth of ~ 4 m in the Mojave Desert, NV (i.e., Gee et al., 1994; Andraski 1997), within the relatively short time period of the simulation. The lateral extent of the domain was set to 4 m (or 2 m), which is the approximate average interval (or half mean interval) between L. Tridentada plants at our
field sites. It was further assumed that flow and transport behavior was symmetric about each plant; thus, the centerline of a plant could be used as a no-flow boundary.

The soil materials used in this model were visually identified in four layers in the upper 2 m of the profile, which was further classified into 5 layers by more accurate particle size and bulk density analyses (Table 4.1, data from SEPHAS project). In the conceptual and numerical modeling, we assumed that flow through inner pores of gravel particles can be ignored based on the observation that the major compositions of gravels are volcanic rocks with low permeability. Thus, the gravels were excluded from the simulation.

4.2 Numerical Model Description

HYDRUS-2D/3D (Šimůnek et al., 2006) was used in this study to simulate the multiple processes of liquid water flow, chloride transport, heat transport, plant root water uptake, and evaporation from the soil surface.

4.2.1 Water Flow and Plant Root Water Uptake

The governing flow equation in HYDRUS 2D/3D (Šimůnek et al., 2006) is given by the following modified form of the Richards' equation:

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i} \left[ K \left( K_{ij} \frac{\partial h}{\partial x_j} + K_A \right) \right] - S
\]

where \( \theta \) is the volumetric water content [-]; \( t \) is the time [T]; \( K \) is the hydraulic conductivity [L/T]; \( h \) is the pressure head [L]; \( S \) is a sink term; \( x_i (i=1, 2) \) are the spatial coordinates; \( K_{ij} \) are components of a dimensionless anisotropy tensor \( K_A \), though we assume the domain contains isotropic medium. Equation (1) is applied to planar flow in a
vertical cross-section, so $x_1=x$ is the horizontal coordinate and $x_2=z$ is the vertical coordinate, the latter taken to be positive upward.

The sink term, $S$, in (1) equation represents the uptake of soil water by plants and is defined by Feddes et al. (1978) as:

$$S(h) = \alpha(h)S_p$$

where $\alpha [-]$ is a water stress response function of soil-water pressure head $h [L]$ (Figure 4.1), and $S_p [T^{-1}]$ is the potential water uptake rate. Water uptake is assumed to be zero when $h$ is close to zero or when $h<h_4$ (wilting point). Water uptake is optimal when $h$ is between $h_2$ and $h_3$. Parameter $h_3$ is an atmospheric water-demand dependent value, which varies with $T_p [L/T]$ (potential transpiration rate). In this study, $h_4$ is set at -400 m, because the wilting point of dominant species in study area, *Larrea Tridentada*, can be reached as low as -800 m.

The potential water uptake rate, $S_p [T^{-1}]$, over a non-uniformly distributed root zone can be calculated as follows (Vogel, 1987):

$$S_p = b(x,y,z)S,T_p$$

where $b(x,y,z) [L^{-2}]$ is the normalized water uptake distribution, $S_t [L]$ is the width of the soil surface associated with transpiration, and $T_p [L/T]$ is the potential transpiration rate. Kemp et al. (1997) described the one-dimensional root zone distribution for *L. tridentada*, and Stevenson et al. (2009) provided two-dimensional root patterns of *L. Tridentada* in Mojave Desert soils. We standardized the root distribution of *L. tridentada* by normalizing values of root distribution described in Stevenson et al. (2009) into similar values used in Kemp et al. (1997). For examples, a root distribution of 5 – 10 was normalized to 0.2; and a root distribution of 10 – 15 was normalized to 0.3. The
standardized root distribution was shown in Table 4.2. It is important to note that the root
distribution of *L. tridentada* differs from plant to plant; thus, the final root distribution
used in the model is only conceptually represented. Furthermore, water uptake
distribution will be normalized to unity across the flow domain by HYDRUS 2D/3D
(Šimůnek et al., 2006). Hence, the standardization of root uptake distribution will not
influence the simulation results.

The van Genuchten (1980) and Mualem (1976) equations used for hydraulic
properties are given as follows:

\[
\frac{\theta(h)}{\theta_s - \theta_r} = \left[1 + \left(\frac{\alpha h}{n}\right)^n\right]^{-1}
\]

\[
K(h) = K_s S_e^m [1 - (1 - S_e^{1/m})^m]^2
\]

\[
m = 1 - \frac{1}{n} \quad n > 1
\]

\[
S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}
\]

where \(\theta_r\) [-] is volumetric residual water content, \(\theta_s\) [-] is the volumetric saturated water
content, \(\alpha\) [L^{-1}] and \(n\) [-] are parameters that affect the shape of the water retention curve.

The soil hydraulic properties (van Genuchten, 1980) were estimated using the
pedotransfer functions method (Schaap et al., 1998) using soil texture and bulk density,
which were obtained from the *SEPHAS* investigation. The predicted soil hydraulic
properties are listed in Table 4.1. To improve convergency of the model, \(n\) values in the
top 3 layers were decreased from 2.79, 3.48, and 3.10 to 1.42 (to widen the pore size
distribution and make the dewatering more even), as used in the paleofluxes simulation in Amargosa Desert Research Site (ADRS) (Scanlon et al., 2003).

4.2.2 Solute Transport

The governing solute transport equation for chloride in HYDRUS 2D/3D (Šimůnek et al., 2006) is the advection-dispersion equation, which can be represented as follows:

\[
\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial x_i} \left( \theta D_{ij}^{w} \frac{\partial c}{\partial x_j} \right) - \frac{\partial q c}{\partial x_i}
\]

(8)

where \( \theta \) [-] is volumetric soil water content, \( c \) [M/L^3] is the solute concentration, \( t \) is time, \( q \) [L/T] is the volumetric flux density, and \( D_{ij}^{w} \) [L^2/T] is the liquid dispersion coefficient tensor, which is given by Bear (1972) as follows:

\[
\theta D_{ij}^{w} = D_T |q| \delta_{ij} + (D_L - D_T) \frac{q_i q_j}{|q|} + \theta D_w \tau_w \delta_{ij}
\]

(9)

where \( D_T, D_L \) [L] are the transverse and longitudinal dispersivities; \( q \) [L^2/T] is the absolute value of fluid flux density; \( D_w \) [L^2/T] is the molecular diffusion coefficient in free water; \( \delta_{ij} \) [-] is the Kronecker delta function, which equals 1 when \( i = j \), and equals 0 if \( i \neq j \); and \( \tau_w \) [-] is a liquid tortuosity factor described by Millington and Quirk (1961) as:

\[
\tau_w = \frac{\theta^{7/5}}{\theta_s^{2}}
\]

(10)

A few assumptions were used in this study when applying this model: 1) no chloride “sinks” (i.e., no mineral dissolution or formation) exists in the soil profile; 2) chloride only transports in the liquid phase; 3) effects of salt concentration gradient can
be ignored given low clay contents (less than 8%, Table 4.1) in the studied soil profiles (Hillel, 1998).

A constant chloride concentration in precipitation, 0.0016 mg/cm³, is used over the entire simulation period (Scanlon et al., 2003). The parameters \( D_L \) and \( D_T \) in equation 8 are set as 100 cm and 10 cm, respectively, based on soil profile scale and ratio of \( D_L \) over \( D_T \) (Domenico and Schwartz, 1998; de Vos et al., 2002). The diffusion coefficient of chloride in free water is set as 1.3 cm³d⁻¹ (Cook et al., 1992).

4.2.3 Heat Transport

Without considering the effects of water vapor diffusion, the governing equation for heat transport in HYDRUS-2D/3D is given by (Sophocleous, 1979) as follow:

\[
C(\theta) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i} \left( \lambda_{ij}(\theta) \frac{\partial T}{\partial x_j} \right) - C_w q_i \frac{\partial T}{\partial x_i}
\]

where \( C(\theta) \) and \( C_w \) [ML⁻¹T⁻²K⁻¹] are the volumetric heat capacities of the porous medium and water, which are defined as the product of gravimetric heat capacity and bulk density; \( T \) [T] is temperature; \( q_i \) [L/T] is the absolute value of water flux; and \( \lambda_{ij}(\theta) \) [ML⁻¹T⁻³K⁻¹] is apparent thermal conductivity of the soil. Similar to the liquid dispersion coefficient tensor, \( \lambda_{ij}(\theta) \) can be described as follows (Šimůnek and Suarez, 1993):

\[
\lambda_{ij}(\theta) = \lambda_T C_w |q| \delta_{ij} + (\lambda_L - \lambda_T) C_w \frac{q_i q_j}{|q|} + \lambda_0(\theta) \delta_{ij}
\]

where \( \lambda_T \) and \( \lambda_L \) [L] are transversal and longitudinal thermal dispersivities, respectively; \( \lambda_0(\theta) \) [ML⁻¹T⁻³K⁻¹] is the thermal conductivity of porous medium (solid and water) without the presence of flow; and \( \delta_{ij} \) [-] is the Kronecker delta function, which is
similar to that used in the solute transport calculations. Thermal parameters for sand (Chung and Horton, 1987) were used in the model and set in HYDRUS 2D/3D.

4.3 Initial and Boundary Conditions

In this study, the same pressure head, chloride concentration of pore water and temperature (when considering heat transport) were specified for all nodes as the initial condition.

The top boundary was set as atmospheric boundary conditions. A solute flux boundary (third-type, Cauchy) was set as the upper and bottom boundary condition when considering solute transport to obtain mass conservative simulations (van Genuchten and Parker, 1984). The upper and bottom boundary was set as a temperature boundary (first-type, Dirichlet) condition, which specify given temperatures in the input surface (van Genuchten and Parker, 1984) for Case 7 (heat transport was considered only in this case). The vertical boundaries were set as no flux for all cases.

4.3.1 Initial Conditions

The initial pressure head in the domain is set as -1000 cm, for the dry conditions after Pleistocene in the Mojave Desert (i.e. Hostetler and Benson 1990). The estimated surface soil age is less than 1200 yr; hence we assume the initial chloride concentration of pore water is equal to zero. The initial temperature in the studied domain is set to 20 ℃, the default value in HYDRUS 2D/3D, when heat transport is considered.

4.3.2 Fixed Boundary Conditions (sides and bottom)

A free drainage bottom boundary is chosen because a zone with unit gradient is present below the active root zone or shallow fluctuation zone (Nimmo et al., 1994). The
temperature at the bottom boundary (22.3 °C) is calculated based on a geothermal gradient of 40 °C/km (Scanlon et al., 2003) and the 26.5 °C of groundwater temperature at 110-m depth in the Mojave Desert (Walvoord et al., 2004).

4.3.3 Upper Boundary Condition

While the side and bottom boundary were set as fixed to represent field conditions, the upper boundary was varied to reflect natural conditions. In this study, daily-distributed rainfall (except Case 8, precipitation was applied uniformly throughout each day such that the sum of water added equals total recorded precipitation for that day), potential evaporation, and potential transpiration were generated as input file.

4.3.3.1 Precipitation Record

Climate change can significantly influence water balance in certain regions. In the last 10 ka (thousand years), arid conditions similar to today are indicated by paleoclimatic records in the western USA, such as lake levels (i.e., Jannik et al., 1991; Morrison, 1991; and Benson, 1991) and climate model simulations (i.e., Hostetler and Benson, 1990). Hence, we constructed the precipitation regime over the past 100 years by simply duplicating the daily records of the last 23 years of climatological observations taken during the previous 77 years (10/1931-09/2008). The precipitation records are from the Boulder City meteorological station (261071), which is only 15 km away from the field site. The annual rainfall during the 77-year period (10/1931 – 09/2008) is shown in Figure 4.2. Precipitation during 10/1931 – 07/2004 were taken from the National Ocean and Atmospheric Administration (NOAA), and records used for the period 08/2004 – 09/2008 are from the Western Regional Climate Center (WRCC) and Desert Research Institute in Reno, Nevada. A total of 863 missing records in the NOAA database were
filled by taking the median of the nearest 10 years of records. As an example, precipitation in June, 1979 was filled with the median of June precipitation data observed during 1974-1978 and 1980-1984. The annual rainfalls over the 77 water years range from 1.55 cm (10/1/2001 – 9/30/2002) to 30.75 cm (10/1/2004 – 9/30/2005). Several droughts and wet conditions are roughly identified from the annual rainfall records: 1932-1941 (wet), 1942-1974 (dry, except for several wet years), 1974-1998 (wet), and 1999-2008 (dry, except for an extremely wet water year, 2005). The wet-dry alternations are approximately contemporaneous with the precipitation variations reported from the Mojave Desert Regions (USGS, 2004). In general, no obvious long-term trend is examined from Figure 4.2.

4.3.3.2 Construction of Potential Evapotranspiration Records

The dataset for potential evapotranspiration (PET), the environmental demand for evapotranspiration, is generated using desert plant phenology and the method described in Young et al. (2006). Soil evaporation (PE) is taken as a straight percentage of PET (20%). The potential transpiration (PT) is generated as the sum of PT for three dominant species, evergreen shrubs, winter annuals, and drought deciduous shrubs. Because no directly detailed research on seasonal plant coverage is available in Eldorado Valley, we use the plant community occurring from California to Southern Nevada (Young et al., 2006) to generate PT in our simulation. The PT for each species is calculated based on the activity period for the growth forms as shown in Table 4.3 (Young et al., 2006). The PT of annuals and drought deciduous shrubs is decreased or zeroed during the years when winter precipitation is less than 26.8 mm (Young et al., 2006), because winter rainfall is
essential for seed germination of these species. A 20% plant cover estimated from field observation in Eldorado Valley is used to create the PT records.

4.3.3.3 Estimation of Temperature

The monthly average air temperatures in Boulder City during 08/1999 – 06/2009 (WRCC and DRI) are used to generate the temperature at the atmospheric boundary.

4.4 Case Analysis

We examined the impact of plant uptake and several environmental factors on water flow and chloride transport, including density of precipitation (climate), surface runoff, heat transport, and compressed daily precipitation. The characteristics of simulation cases are summarized in Table 4.3. Although we describe the heat transport above, it is important to note that the heat transport process was only considered in Case 7.

4.4.1 Cases 1 and 2, Wet versus Dry Climates, and Symmetry

Cases 1 and 2 are set up to examine the effects of climate condition (wet or dry) on water flow and chloride transport, using a 4×4 m² rectangular vertical plane as the domain. We assume two plants are symmetrically distributed on either side of the domain, with bare soils in the middle (Figure 4.3). The 4-m width of the domain is the average interval between two adjacent *L. Tridentada* shrubs measured in Eldorado Valley in summer 2008. The spatial root water uptake function (Figure 4.2) was based on the standardized root density distributions described in Table 4.2 (from Kemp et al., 1997 and Stevenson et al., 2009). Cases 1 and 2 are 5-year simulations, with wet conditions in Case 1 (Oct. 1979 to Sep. 1984) and dry conditions in Case 2 (Oct. 1998 to Sep. 2003).
The annual rainfall in Case 1 ranged from 15.28 to 26.28 cm, with a single deep-wetting event (9.3 cm daily rainfall) in the fifth water year (26.28 cm annual rainfall). In contrast, Case 2 is characterized by much lower annual rainfall amount, ranging from 1.55 to 11.75 cm (Figure 4.4).

The simulations in Cases 1 and 2 were also used to investigate symmetry within the flow domain. Using those results (described below), all subsequent simulations were performed on a 2×4 m² domain with no flow boundaries along both sides (Figure 4.5). By reducing simulation size, computational speed was greatly enhanced.

4.4.2 Cases 3 and 4, Influence of Root Uptake

Case 3 examines the influence of root water uptake on paleofluxes over 100 years. Case 4 examines paleofluxes for bare soil conditions.

4.4.3 Cases 3, 5, and 6, Effects of Microtopography

Three 100-year case studies (Cases 3, 5, and 6) are used to test the effects of topography (flat, bar, and swale) on paleofluxes, respectively. As described above, some precipitation falling in the bar area will flow into an adjacent swale, decreasing the precipitation amount in the bar. Thus, different precipitation regimes were developed for these three cases: one with original precipitation amounts (control, Case 3), the next case with 1/2 precipitation amount (bar area, Case 5), and the final treatment with double the precipitation amount (swale area, Case 6).

4.4.4 Cases 3 and 7, Impact of Thermal Transport

The impact of heat transport will be investigated by comparing results between Cases 3 and 7, in which heat transport is considered. In Case 3, only isothermal condition was considered. In contrast, thermally driven liquid water flow was allowed in Case 7.
4.4.5 Cases 3 and 8, Effects of Compressed Precipitation and PET

In Case 8, daily precipitation is forced randomly into one of four six-hour periods: 0:00-6:00, 6:00-12:00, 12:00-18:00, 18:00-24:00. The PET is only distributed between 6:00-18:00.

4.5 Results

The simulated results are presented as 2D panels of soil-water potential, volumetric water content, pore water chloride concentration, and velocity vector at selected print times. Additionally, to examine simulated water contents or chloride concentrations through time, we included several observation nodes at variable distances to the root zone. The simulated pore water chloride concentrations (mg/cm$^3$) are converted into soil chloride concentrations (mg/kg-soil or ppm), to be consistent with measured data by using the following equation:

$$ c = \frac{c_{pw} \times \theta_v}{\rho_b} \times 1000 \quad (13) $$

where $c$ is chloride concentration in bulk soil, $c_{pw}$ is pore water chloride concentration, $\theta_v$ is volumetric water content, and $\rho_b$ is bulk density.

4.5.1 Cases 1 and 2 - Wet versus Dry Climate

We compares soil chloride concentrations between Cases 1 and 2 after the fifth simulation year (Figure 4.6). The results show higher chloride concentrations in root zones than in intercanopy soils. The chloride concentrations in Case 2 are much higher than those in Case 1 (above around 220-cm depth). However, the chloride is pushed into deeper soils in Case 1, and forms into an intermediate chloride zone between 120- and
160-cm depth. The occurrence of this intermediate-depth chloride zone directly corresponds to the change in soil properties at the fourth layer (120 to 160 cm).

Figure 4.7 presents the velocity vectors after the 5th simulation year in Case 1 (left panel) and Case 2 (right panel). The densities of vectors in Case 1 are much higher than those observed in Case 2, indicating more active water movement after the wetter water year in Case 1. In Case 2, the dry soil conditions formed after several low rainfall water years forced the water to move toward root zone to support the water needs of the shrub.

The simulated soil chloride concentrations (Cl\textsuperscript{-}) in Case 1 at the beginning (Oct. 1, 1983) and end (Sep. 30, 1984) of a wet year are shown in Figure 4.8. Both diagrams in this figure show that chloride accumulated toward root zones (sides of the domain) and decreased toward bare soil areas (middle of the domain). In the beginning of this wet water year, “chloride bulges” formed in the near surface layers (0-50 cm below surface) within root zones. At the end of this water year, however, the “bulges” are transferred into deeper layers (around 100 cm).

The simulated velocity vectors in the beginning and end of the wet year are presented in Figure 4.9. The velocity vectors shown in the left diagram correspond to several medium precipitation events. In the near surface layers, water moves downward, and eventually water moves toward the center of the root zone. In contrast, the right diagram shows water moving upward in layers above 120 cm, and downward in soils below it. The results indicate that water stored over a wet water year evaporates back to atmosphere in the near-surface soil layers, but will percolate downward in deeper soils, leading to the formation of an intermediate chloride zone (Figure 4.8).
The two-dimensional diagrams presented above show apparent symmetrical patterns between root zones of two shrubs. We used five observation nodes in Cases 1 and 2 at the same depth (50 cm), placed at variable distances to root zones, to observe how chloride concentrations change with time (Figure 4.10). Nodes 1 and 5 are located at the left and right zones of the domain, 10 cm to the center of root zone. Nodes 2 and 4 are at the edges of root zones (left and right, respectively), and Node 3 is located in the middle of domain (bare soil). Figure 4.11 shows the plots of soil chloride concentrations for Node 1 versus Node 5 (C1 versus C5), and for Node 2 versus Node 4 (C2 versus C4). The plotted points are located at 45 degree lines, with $R^2$ values of 0.9991 and 0.9981 for Cases 1 and 2, respectively. These results confirmed that the simulated results are symmetrical between root zones. Hence, we simplified the remainder of the simulations by reducing the domain into a $2 \times 4 \text{ m}^2$ grid with one shrub placed at the upper left side of the domain.

4.5.2 Effects of Root Water Uptake

The simulated soil chloride concentrations at the 100th simulation year in Cases 3 and 4 are shown in Figure 4.12. Obviously, the presence of root water uptake significantly impacts chloride distribution in the soil domain. First, with the presence of root water uptake, soil chloride accumulates toward root zones, leading to high concentration gradients from the centroid of the root zone toward bare soils (Figure 4.12, left panel). In comparison, chloride is more evenly distributed in the domain without root water uptake in Case 4 (Figure 4.12, right panel). Second, the average soil chloride concentration in Case 3 is much higher (4 to 8 times) than that observed in Case 4. The results indicate that more water moves out the 4-m deep domain through free drainage.
without root water uptake. In contrast, with the presence of root water uptake, more soil moistures remains in the near surface horizons, returning back to the atmosphere through evaporatranspiration, leading to the formation of chloride bulges in near surface layers. Furthermore, the intermediate chloride zone shown in Case 1 (Figure 4.6) is also observed in Cases 3 and 4 (Figure 4.12). The transition zone is between 120 and 160 cm, similar to that observed in Case 1.

The results show the simulated velocity vectors at the 100th simulation year in Case 3 (left panel) and Case 4 (right panel) in Figure 4.13. With the presence of plant water uptake, water flows toward the root zone. In comparison, no lateral flow is present in Case 4 without root water uptake. In addition, the density of downward water flow is relatively smaller in Case 3, indicating that less water moved into deeper soils through free drainage.

Three observation nodes used in Case 3 at the same depth are placed at variable distance to the root zone (Figure 4.14). Node 1 (C1) is in the centroid of the root zone, Node 2 (C2) is located at the edge of root zone, and Node 3 (C3) is in bare soil. The simulated soil chloride concentrations in observation nodes (Figure 4.15) are similar. Concentrations increase with time in the first 70 years, and then vary with time. The results suggest that around 70 years are needed for the system to reach dynamic equilibrium. Behaviors afterwards are then dominated by climatic variability. Soil chloride concentrations are correlated with wet and dry water years, sharply decreasing after wetter years (Figure 4.15). For example, the heaviest daily rainfall event (9.3 cm/day) occurred on Aug. 14, 1984 (75.871 year), leading to a significant decrease of
chloride concentration at 50-cm depth. These results suggest that chloride is re-dissolved and then transported downward following this event.

The simulated soil water content at three observation nodes are shown in Figure 4.16. Spatially, the moisture contents increase with the increase of distance to the centroid of root zone (from C1 to C3). Temporally, the soil moisture content varies with time. Similar to chloride concentrations, the variations of soil moisture content are closely correlated with the variability of rainfall (Figure 4.16).

In general, the chloride concentrations decrease with an increase of distance from the center of the root zone. The results show the strength of root water uptake and how that strength decreases from the center of the root mass. In addition, although the overall patterns of soil chloride concentrations in these nodes are similar, the patterns varied after 70 years. As shown in Figure 4.17, the correlations of soil chloride concentrations simulated in the last 30 years between C1 and C2 are higher than those between C1 and C3, with $R^2$ values of 0.5292 and 0.3561, respectively. This result indicates that the influence of root uptake on chloride transport decrease with the increase of distance toward the centroid of root zones.

4.5.3 Impact of Topography

Three cases are developed to examine the effects of topography on paleofluxes by resetting precipitation depending on topographic locations. Here, Case 3 is the control case with original precipitation, and Case 5 has 1/2 precipitation amount to approximate the reduced infiltration on bars due to runoff. Conversely, the precipitation amount for Case 6 is doubled to approximate the effects of runon into swale locations.
As shown in Figure 4.18, the simulated soil chlorides in Case 5 (1/2 precipitation amount) were concentrated at the similar chloride accumulation depth simulated in Case 3 (one precipitation amount). These results indicate that less chloride flows out the domain through free drainage. By comparison, the overall concentrations of chloride in Case 6 (2 precipitation amount) were much lower than Case 1 (one precipitation amount), even though we doubled the chloride source into the domain through rainfall.

Ratios of accumulative drainage over infiltration were used to indicate percentage of water flow out the soil domain. As shown in Figure 4.19, the percentage of accumulated drainage to infiltration (up to 17%) in Case 6 is much higher than in the control Case 3 (up to 1.6%). The wetting front, which is indicated by sharp increase of ratios of drainage over infiltration, reaches the bottom after 6.2 years in Case 5 and after 12.0 years in Case 3. In contrast, the wetting front does not reach the bottom of the domain in Case 5, even after 100 years.

4.5.4 Impacts of Thermal Transport

The simulated soil chloride concentrations in Case 7 are the same with Case 3; given that HYDRUS 2D/3D does not simulate advective vapor transport, these results are not surprising. To further examine this issue, we set up two 100-year simulations in HYDRUS 1D using the same properties and input parameters as in the 2D simulations. Two case studies were run. Case 1D-1 was run without heat transport and Case 1D-2 was run with heat and vapor water flow. The simulated soil chloride concentrations at the 100th simulation year are plotted in Figure 4.20. The similar results in these two cases indicate that the impact of thermal transport and vapor water flow on chloride redistribution in arid soils is insignificant given the time period used in this study.
4.5.5 Impact of Compressed Precipitation and PET

The simulated soil chloride concentrations at the 100\textsuperscript{th} simulation year in Cases 3 and 8 are standardized into unity by dividing the maximum values in each case. The standardized results are plotted in Figure 4.21. The general patterns of standardized soil chloride are similar in Cases 3 and 8. Soil chloride concentrates toward root zones and accumulates in near-surface soils, with an intermediate zone located at 120 – 160 cm depth. However, relative concentrations in Case 8 are lower than those observed in Case 3, suggesting that the chloride mass is redistributed more fully throughout the soil profile and transported downward out of the domain. The results are similar to those reported for Case 6 (double precipitation). Although the accumulated PET could concentrate more chloride in near-surface layers through daily evaporation, the compressed rainfalls transport more chloride into relatively deeper layers in Case 8. The results suggest that the effects of compressed rainfall are stronger than the impact of compressed PET.
Table 4.1 Soil physical and hydraulic properties in Eldorado Valley, NV
(van Genuchten, 1980 and Scanlon et al., 2003)

<table>
<thead>
<tr>
<th>Top Depth</th>
<th>Bottom Depth</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>Bulk Density</th>
<th>$\theta_t$</th>
<th>$\theta_s$</th>
<th>alpha</th>
<th>$n$</th>
<th>Ks</th>
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<td>%</td>
<td>%</td>
<td>%</td>
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<td>cm$^3$/cm$^3$</td>
<td>cm$^3$/cm$^3$</td>
<td>-</td>
<td>-</td>
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</tr>
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<td>3.5</td>
<td>1.4</td>
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<td>0.033</td>
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<tr>
<td>120</td>
<td>160</td>
<td>91.6</td>
<td>5.5</td>
<td>2.8</td>
<td>1.71</td>
<td>0.046</td>
<td>0.325</td>
<td>0.036</td>
<td>2.70</td>
<td>275</td>
<td>0.5</td>
</tr>
<tr>
<td>160</td>
<td>400</td>
<td>78.2</td>
<td>13.7</td>
<td>8.0</td>
<td>1.74</td>
<td>0.041</td>
<td>0.322</td>
<td>0.045</td>
<td>1.54</td>
<td>37</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 4.2 Two dimensional standardized root distribution of *Larrea Tridentada*
(After Kemp et al., 1997 and Stevenson et al., 2009)

<table>
<thead>
<tr>
<th>Depth -- cm --</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-10</td>
</tr>
<tr>
<td>0-10</td>
<td>0</td>
</tr>
<tr>
<td>10-20</td>
<td>0.1</td>
</tr>
<tr>
<td>20-40</td>
<td>0.2</td>
</tr>
<tr>
<td>40-60</td>
<td>0.3</td>
</tr>
<tr>
<td>60-80</td>
<td>0.3</td>
</tr>
<tr>
<td>80-100</td>
<td>0.1</td>
</tr>
<tr>
<td>100-400</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 4.3 Activity period for components of potential evapotranspiration.

<table>
<thead>
<tr>
<th>Component of PET</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil evaporation</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Winter annuals</td>
<td>20</td>
<td>20</td>
<td>20-37</td>
<td>20-37</td>
<td>20-37</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Drought-deciduous shrubs</td>
<td>0</td>
<td>0</td>
<td>0-17</td>
<td>0-17</td>
<td>0-17</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total possible uptake</td>
<td>65</td>
<td>65</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>65</td>
<td>65</td>
</tr>
</tbody>
</table>

Table 4.4 Characteristics of simulation cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Domain (m²)</th>
<th>Time (years)</th>
<th>Root water uptake</th>
<th>Climate</th>
<th>Compressed Daily Precipitation</th>
<th>Heat Transport</th>
<th>Surface Runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4x4</td>
<td>5</td>
<td>Yes</td>
<td>Wet</td>
<td>Daily</td>
<td>Isothermal</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>4x4</td>
<td>5</td>
<td>Yes</td>
<td>Dry</td>
<td>Daily</td>
<td>Isothermal</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>2x4</td>
<td>100</td>
<td>Yes</td>
<td>N.A.</td>
<td>Daily</td>
<td>Isothermal</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>2x4</td>
<td>100</td>
<td>NO</td>
<td>N.A.</td>
<td>Daily</td>
<td>Isothermal</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>2x4</td>
<td>100</td>
<td>Yes</td>
<td>N.A.</td>
<td>Daily</td>
<td>Isothermal</td>
<td>1/2 Precipitate</td>
</tr>
<tr>
<td>6</td>
<td>2x4</td>
<td>100</td>
<td>Yes</td>
<td>N.A.</td>
<td>Daily</td>
<td>Isothermal</td>
<td>2 Precipitate</td>
</tr>
<tr>
<td>7</td>
<td>2x4</td>
<td>100</td>
<td>Yes</td>
<td>N.A.</td>
<td>Daily</td>
<td>Non-Isothermal</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>2x4</td>
<td>100</td>
<td>Yes</td>
<td>N.A.</td>
<td>6 Hourly</td>
<td>Isothermal</td>
<td>No</td>
</tr>
</tbody>
</table>
Figure 4.1 Schematic of plant water stress response function.

(After Feddes et al., 1978 and Šimůnek and Hopmans, 2009)

Figure 4.2 Annual rainfalls during 1931/10 to 2008/09 recorded in Boulder City, NV
Figure 4.3 Domain geometry and spatial root distribution for Cases 1 and 2.

Figure 4.4 Annual rainfalls used in Case 1 and 2
Figure 4.5 Domain geometry and root water uptake for cases with $2 \times 4 \text{ m}^2$ area.

Left: with root water uptake; Right: without root water uptake.
Figure 4.6 Simulated soil chloride concentrations in Cases 1 and 2.
Left: Case 1 in wet climatic condition; Right: Case 2 in dry climatic condition.

Figure 4.7 Simulated velocity vectors in Cases 1 and 2.
Left: Case 1 in wet climatic condition; Right: Case 2 in dry climatic condition.
Figure 4.8 Simulated soil chloride concentrations in Case 1.

Left: before a wet year; Right: after the wet year.

Figure 4.9 Simulated velocity vectors in Case 1.

Left: before a wet year; Right: after the wet year.
Figure 4.10 Position of five observation nodes in Cases 1 and 2.

Figure 4.11 Correlation between simulated soil chloride concentrations at observation nodes.
Figure 4.12 Simulated soil chloride concentrations at the 100th year in Cases 3 and 4.

Left: Case 3 with root uptake; Right: Case 4 without root uptake.
Figure 4.13 Simulated velocity vectors at the 100th year in Cases 3 and 4.

Left: Case 3 with root uptake; Right: Case 4 without root uptake.
Figure 4.14 Location of three observation nodes in Case 3.
Figure 4.15 Simulated soil chloride concentrations at three observation nodes in Case 3.

Node 1 (10, 350), Node 2 (100, 350), and Node 3 (190, 350)

Figure 4.16 Simulated soil water content at three observation nodes in Case 3.

Node 1 (10, 350), Node 2 (100, 350), and Node 3 (190, 350)
Figure 4.17 Correlations between C1 and C2, and C1 and C3.
Figure 4.18 Simulated soil chloride concentrations at the 100th year in Cases 3, 5, and 6.

Left: Case 3, control; Middle: Case 5; Right: Case 6.
Figure 4.19 Ratio of accumulated drainage over infiltration in Cases 3, 5, and 6.
Figure 4.20 Simulated soil chloride concentrations at 100th simulation year in 1-D Cases.

Case 1D-1: without vapor water flow; Case 1D-2: with vapor water flow.
Figure 4.21 Standardized soil chloride concentrations at 100\textsuperscript{th} year in Cases 3 and 8.
CHAPTER 5

DISCUSSION AND CONCLUSION

5.1 Chloride Distributions and Paleowater Fluxes

In this study, substantially different chloride profiles between canopy and intercanopy microsites are observed. Under the plant canopies, chloride concentrations increase with depth, following a conservative solute-type profile (concentrations increase with depth to form a bulge at certain depth) with the presence of plants (Schlesinger and Pilmanis 1998; Jobbagy and Jackson 2001). However, chlorides in the intercanopies in the upper 100 cm soils are characterized by much lower concentrations. The results indicate that the laterally spatial heterogeneity of chloride is related to the presence or absence of plant canopies. In a binary system of canopy and intercanopy microsites (i.e., where plants are either present or absent), the different chloride patterns may result from spatial heterogeneity of soil structures and hydraulic properties developed by plant growth in these microsites (e.g., Young et al., 2004; Caldwell et al., 2008). However, the similar soil texture (Figure 3.2) observed between canopy and intercanopy microsites and the weakly developed soil structure at the study site indicates that the different chloride profiles did not result from spatial heterogeneity of soil physical properties. Considering the laterally homogeneous soil texture and structure at the study site, it is suggested that the different chloride distributions between canopy and intercanopy microsites are due to plant root water uptake. In this conceptual model, an extremely negative soil matric potential within root zones is formed by plant water uptake, leading to a lateral matric potential gradient and slow lateral water movement toward root
regions. Adding the precipitation and salt that falls directly on the canopy sites to the water and salt that are transported laterally toward the root zone areas will result in the formation of salt bulges under the plant canopies. The effects of plant cycling or root uptake on nutrient distributions in soils proposed by Schlesinger and Pilmanis (1998) and Jobbagy and Jackson (2001) supported the results we present and conceptual model we proposed.

Other research groups have proposed that chloride bulges in the vadose zone (3-5 m depth or deeper) were triggered by wet to dry climate shift during the Pleistocene to Holocene (i.e., Walvoord et al., 2002a; Walvoord et al., 2003). The young-aged soils (800-1200 years) in this study were formed without significant wet to dry transitions, indicating that the climate shift is not the only explanation for chloride accumulation. Furthermore, Marion et al. (2008) argued that chloride bulges at shallow soils (around 100-cm depth) only represent part of the atmospheric chloride inputs, the majority of which should leach past 100-cm depth.

In our case, chloride mass balance method was used to estimate soil ages in all field sampling sites based on the following assumptions: 1) precipitation was the only chloride input; 2) no chloride leached past 100-cm depth (leading to underestimation); 3) no chloride transported through lateral flow. The soil ages ($t$) were calculated using the following equation:

$$ t = \frac{\sum_{i=1}^{10} [\rho_b \cdot \text{g} \cdot \text{cm}^{-3} \times 10^4 \text{cm}^2 \times 10cm \times (1-%\text{Gravel}) \times c \cdot \text{mg} / \text{kg}]}{100\text{mg} / \text{yr}} $$

(14)

where $\rho_b$ is bulk density; $%\text{Gravel}$ is the mass percentage of gravel; $c$ is chloride concentration in bulk soil; and $100\text{ mg} \cdot \text{m}^2 \cdot \text{yr}^{-1}$ is the average annual chloride flux at
surface boundary (Dettinger, 1989). The annual chloride flux used for age estimates (100 mg.m\(^{-2}\).yr\(^{-1}\)) is much lower than the flux of chloride calculated from annual precipitation and chloride concentration in rainfall used for numerical modeling (220 mg.m\(^{-2}\).yr\(^{-1}\)). It is important to note that the precipitation recorded over the last 77 years in Boulder City can not fully represent the rainfall in the basin of Eldorado Valley over long-term periods (e.g., 1000 years). Hence, we selected the 100 mg annual chloride flux, which was usually used to estimate soil ages over thousands of years in the western USA, for age estimates in our field sites.

As shown in Table 5.1, the estimated ages under the plant canopy B2 (1304 year) is older than the real estimated age (800 – 1200 year), suggesting the lack of chloride bulges in deeper layers. However, the younger estimated ages in the intercanopy profiles suggest the possible formation of chloride bulges at deeper horizons in intercanopy sites, especially given that chloride mass is conserved. This prediction is consistent with observed salt bulges at around 2-m depth in an intercanopy profile near the field sampling site in Eldorado Valley, Nevada. What is unclear, however, is how the salts were accumulating at the deeper layers in intercanopy soil profiles, and where they represent very long term paleoclimatic conditions. The shallow chloride accumulation depth (90-100cm) under plant canopies was also calculated by Yin et al. (2008), who considered Mojave Desert atmospheric and root water uptake conditions, including precipitation events with 100-year recurrence intervals.

In other cases of soils older than those found at our site, chloride bulges could appear to be deeper. The deeper chloride bulge may be associated with deposition of gravels or dust over tens of thousands of years. Moreover, chloride leaching from shallow
soils within root zones to a deeper reservoir during intermittent deep-wetting events could also form deeper chloride bulges observed in older soil profiles (Walvoord et al., 2003).

Although only considering the top 100-cm layers, more chloride exists in soils beneath the plant canopy at site, B2 than can be accounted for by atmospheric inputs over 1200 years (maximum estimated age by field observation). This indicates that a portion of chloride found within root zones was laterally transported from nearby soils. This hypothesis was confirmed by numerical simulation results. In the scenario with coexistence of canopy and intercanopy (i.e., with the presence of root water uptake in part of the domain, such as Case 3), water flowed toward the root zone, leading to the lateral redistribution of chloride in the soil. In comparison, in conditions without the influence of root water uptake (i.e., Case 4), no lateral flow was identified. Hence, the consideration of root uptake effects becomes very important when selecting new soil sampling sites for chemical analyses, especially for water budget and soil age studies by using chloride mass balance methods.

Caldwell et al. (2008) estimated that surface soil hydraulic and physical properties were influenced by proximity to shrubs until a distance of 1.4 times canopy diameter. What is not known, however, is whether the spatial influence of lateral flow due to root water uptake follows this pattern as well. Furthermore, partitioning of water fluxes between soils under canopies and in nearby unvegetated soils is likely to be uneven. Quantifying paleofluxes to estimate future groundwater recharge in arid regions would also need to consider microsite location.
5.2 Nitrate Distributions

Similar to the discussion of chloride, soil nitrate profiles are distributed differently between canopy and intercanopy microsites. Under the plant canopies, NO$_3$-N concentrations follow the accumulation patterns of chloride, instead of progressive nutrient depletion profiles (concentrations are high in near-surface soils and decrease with depth), indicating that the input history, transport behaviors and accumulation times of NO$_3$-N are similar to chloride (Walvoord et al., 2003). However, the NO$_3$-N transport behaviors are more complicated than the transport of chloride because of the existence of biogeochemical pathways for nitrate (Walvoord et al., 2003). Although the general patterns of NO$_3$-N profiles are similar to chloride profiles, the average accumulation depth of NO$_3$-N is shallower than that of chloride, indicating the plant uptake is not the only controlling factor that dominates NO$_3$-N distributions under plant canopies. In this study, NO$_3$-N is accumulated at 45- to 65-cm depth under canopies of the seven *L. tridentada* shrubs. Kemp et al. (1997) reported the same accumulation depth for the roots of *L. tridentada*, which is highest at a depth of 40-60 cm. Our results indicate that NO$_3$-N profiles are coupled to the vertical distribution of root zones. The coupling between root density distribution and NO$_3$-N concentrations was also reported by Somma et al. (1998). These results suggest that microbiological activities (balance between nitrification, denitrification, and assimilation) play important roles in redistributing NO$_3$-N in arid root zones, as summarized by Walvoord et al. (2003). Considering that plant uptake is not the only influence on NO$_3$-N redistribution, microbiological activities might trigger the NO$_3$-N fixation in root zones. Hence, additional NO$_3$-N sources are possible in arid soils, besides the atmospheric input. Additionally, the modest NO$_3$-N
needs of the low productivity desert ecosystems and their low nitrogen retention provide favorable conditions for NO$_3$-N accumulation in arid soils (Marion et al., 2008).

In contrast to canopy sites, only small increases in NO$_3$-N concentrations were observed at depth of 45-55 cm, suggesting little or no influence of root uptake or microbiological activities on NO$_3$-N distributions. Deeper nitrate bulges between 1 and 5 m were reported from previous studies (i.e. Hartsough et al., 2001; Stokstad 2003; Walvoord et al., 2003). Similar to chloride, NO$_3$-N bulges may appear to be deeper because of long-term surface deposition of dust and gravel during soil development processes or leaching of NO$_3$-N from shallow soils to deeper reservoirs during intermittent deep-wetting events (Walvoord et al., 2003).

5.3 Effects of Topography and Plant Ages on Cl$^-$ and NO$_3$-N Distributions

Because of the relatively lower elevation of swale areas (relative to bar areas), they can become collection areas of surface runoff, increasing the effective precipitation during storm events. Moreover, runoff processes can transport gravels into the swale areas or erode fine-grained material from swales, leading to higher gravel contents, as we observed from the intercanopy profiles (Figure 3.5). These aggradation and degradation processes, combined with larger effective precipitation amounts can explain the relatively deeper and larger chloride bulges in the swale areas (Figure 3.9). The similarity of NO$_3$-N profiles between swales and bars indicate that microbiological activities in root zones are more essential than other hydrological or geomorphologic processes for nitrate redistributions. Relatively shallower accumulation depths of soil chloride were also observed from numerical simulation results in Case 5 (half of the precipitation amount
simulated bar areas). However, in the condition with twice the amount of precipitation (simulating swale areas in Case 6), the simulated overall chloride concentrations were relatively lower, given deeper transport of chloride through the bottom boundary. In any cases, quantifying the effective precipitation between bar and swale areas is needed to fully explain the differences in field measured chloride concentrations.

Beneath the plant canopies at site S1, the low gravel contents in surface layers (Figure 3.5) suggest the young age of the overlying plant. The young plant age at site S1 leads to the small chloride and nitrate bulges under plant canopies (Figures 3.9 and 3.12). Weak chloride and nitrate bulges are also observed at site B4 (Figures 3.9 and 3.12). However, the similar patterns of gravel contents on bars prevent us from identifying the plant age by gravel profiles (Figure 3.5).

5.4 Conclusions and Future Recommendations

The conclusions in this study are as follows:

1) Substantially different soil chloride profiles were observed between canopy and adjacent intercanopy microsites, with higher soil chloride accumulated under plant canopies in the upper 100-cm soil.

2) Soil age estimates and 2-D simulation results indicate that the chloride accumulation beneath plant canopies is related to the lateral transport of chloride from nearby soils.

3) Probably deeper and larger chloride “bulges” were observed under canopy profiles in swale areas. We explain this occurrence as the result of either higher effective precipitation or aggradation processes of gravel deposition triggered by runoff, or a combination of both.
4) Although relatively deeper accumulation depths of soil chloride were also observed from numerical simulation results in the case study with double precipitation amount, quantifying the effective precipitation between bar and swales areas is needed to fully explain the differences in field-measured chloride concentrations.

5) Similar to chloride, the nitrate accumulated beneath the plant canopies. However, the relatively shallower accumulation depths, and the coupling with vertical distribution of root density indicates that microbiological activities play important roles in redistributing NO$_3$-N in arid root zones. Furthermore, the similarity of NO$_3$-N profiles between swales and bars indicated that microbiological activities in root zones are more essential than other hydrological or geomorphologic processes for nitrate redistributions.

In the future, accounting for the range of spatial influence of lateral flow on water partitioning between canopies and adjacent intercanopies is important when selecting soil sampling sites for estimating water budgets and ages using chloride mass balance methods. Furthermore, mapping the spatial distribution of nitrate and root properties is also important for understanding the nitrate migrations in arid soils, which may be further used to estimate the nitrate budgets in the desert.
Table 5.1 Estimation of soil ages by chloride mass balance approach.

Value of chloride flux at surface boundary is from Dettinger (1989)

<table>
<thead>
<tr>
<th>Sampling Site</th>
<th>Accumulated Cl in the Upper 1-m Profile</th>
<th>Cl Flux at Surface Boundary</th>
<th>Estimated Ages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Under Canopy</td>
<td>Inter-canopy</td>
<td>mg m(^{-2})</td>
</tr>
<tr>
<td>N.A.</td>
<td>92370</td>
<td>821</td>
<td>100</td>
</tr>
<tr>
<td>B1</td>
<td>130405</td>
<td>2912</td>
<td>100</td>
</tr>
<tr>
<td>B2</td>
<td>35437</td>
<td>594</td>
<td>100</td>
</tr>
<tr>
<td>B3</td>
<td>9083</td>
<td>783</td>
<td>100</td>
</tr>
<tr>
<td>B4</td>
<td>8984</td>
<td>783</td>
<td>100</td>
</tr>
<tr>
<td>S1</td>
<td>92283</td>
<td>416</td>
<td>100</td>
</tr>
<tr>
<td>S2</td>
<td>20704</td>
<td>665</td>
<td>100</td>
</tr>
</tbody>
</table>
APPENDIX A TABLE

Table I Summary of determined soil texture and concentrations of Cl and N.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Ave Depth cm</th>
<th>Cl- mg/kg-soil</th>
<th>NO3-N mg/kg-soil</th>
<th>Gravel%</th>
<th>Sand%</th>
<th>Silt+Clay%</th>
<th>Total%</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1I1</td>
<td>5</td>
<td>1.449</td>
<td>n.a.</td>
<td>19.25%</td>
<td>96.43%</td>
<td>3.57%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1I2</td>
<td>15</td>
<td>0.219</td>
<td>n.a.</td>
<td>6.20%</td>
<td>96.17%</td>
<td>3.83%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1I3</td>
<td>25</td>
<td>0.565</td>
<td>n.a.</td>
<td>11.70%</td>
<td>96.53%</td>
<td>3.47%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1I4</td>
<td>35</td>
<td>0.066</td>
<td>n.a.</td>
<td>7.62%</td>
<td>97.17%</td>
<td>2.83%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1I5</td>
<td>45</td>
<td>0.081</td>
<td>n.a.</td>
<td>13.53%</td>
<td>96.87%</td>
<td>3.13%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1I6</td>
<td>55</td>
<td>1.549</td>
<td>n.a.</td>
<td>17.43%</td>
<td>98.21%</td>
<td>1.79%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1I7</td>
<td>65</td>
<td>1.263</td>
<td>n.a.</td>
<td>44.48%</td>
<td>97.71%</td>
<td>2.29%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1I8</td>
<td>75</td>
<td>0.023</td>
<td>n.a.</td>
<td>67.39%</td>
<td>98.22%</td>
<td>1.78%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1I9</td>
<td>85</td>
<td>0.203</td>
<td>n.a.</td>
<td>44.72%</td>
<td>98.87%</td>
<td>1.13%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1I10</td>
<td>95</td>
<td>0.261</td>
<td>n.a.</td>
<td>38.93%</td>
<td>97.42%</td>
<td>2.58%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1C1</td>
<td>5</td>
<td>22.810</td>
<td>n.a.</td>
<td>8.51%</td>
<td>97.34%</td>
<td>2.66%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1C2</td>
<td>15</td>
<td>4.110</td>
<td>n.a.</td>
<td>5.80%</td>
<td>97.69%</td>
<td>2.31%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1C3</td>
<td>25</td>
<td>4.743</td>
<td>n.a.</td>
<td>5.11%</td>
<td>97.96%</td>
<td>2.04%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1C4</td>
<td>35</td>
<td>5.751</td>
<td>n.a.</td>
<td>5.66%</td>
<td>98.43%</td>
<td>1.57%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1C5</td>
<td>45</td>
<td>9.078</td>
<td>n.a.</td>
<td>11.88%</td>
<td>97.82%</td>
<td>2.18%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1C6</td>
<td>55</td>
<td>48.362</td>
<td>n.a.</td>
<td>39.94%</td>
<td>97.66%</td>
<td>2.34%</td>
<td>100.00%</td>
</tr>
<tr>
<td>B1C7</td>
<td>65</td>
<td>111.687</td>
<td>n.a.</td>
<td>50.59%</td>
<td>97.63%</td>
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<td>100.00%</td>
</tr>
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</table>
APPENDIX B FIGURES OF SIMULATION RESULTS

Case 1 at the 5\textsuperscript{th} simulation year
Case 2 at the 5\textsuperscript{th} simulation year
Case 3 at the 100\textsuperscript{th} simulation year
Case 4 at the 100th simulation year
Case 5 at the 100\textsuperscript{th} simulation year
Case 6 at the 100\textsuperscript{th} simulation year
Case 7 at the 100th simulation year
Case 8 at the 100\textsuperscript{th} simulation year
REFERENCES


DOE, 1996, Final Environmental impact statement for the Nevada Test Site and off-site locations in the state of Nevada p. 4-217-275


NOAA http://cdo.ncdc.noaa.gov/pls/plclimprod/poemain.accessrouter?datasetabbv=SOD


Scanlon, B. R., and Goldsmith, R. S., 1997, Field study of spatial variability in
unsaturated flow beneath and adjacent to playas, Water Resour. Res., 33, 2239–
2252.

Scanlon, B. R., Tyler, S. W. and Wierenga, P. J. 1997, Hydrologic issues in semiarid,
unsaturated systems and implications for contaminant transport, Rev. Geophys., 35,
461–490.

Scanlon, B. R., Keese, K., Reedy, R. C., Simunek, J., and Andraski, B. J., 2003,
Variations in flow and transport in thick desert vadose zones in response to
paleoclimatic forcing (0–90 kyr): Field measurements, modeling, and uncertainties,


plant water relations, erosion, and soil water percolation on a Mojave Desert


Water Planning Report 3, Nevada Department of Conservation and Natural
Resources, Division of Water Resources, State of Nevada, Carson City, NV.

two-dimensional variably saturated water flow, heat transport, carbon dioxide
production and transport, and multicomponent solute transport with major ion
equilibrium and kinetic chemistry, Version 1.1, Research Report No. 128, U. S. Salinity Laboratory, USDA, ARS, Riverside, CA.


WRCC and DRI (CEMP), http://www.cemp.dri.edu/cgi-bin/cemp_stations.pl?stn=boul


VITA

Graduate College
University of Nevada, Las Vegas

Wenming Nie

Local Address:
   4566 Maxwell Peak CT
   Las Vegas, NV 89139

Degrees:
   Bachelor of Science, Geology, 2002
   China University of Geosciences, Wuhan, China

   Master of Science, Geochemistry, 2005
   Nanjing University, China

Special Honors and Awards:
   NSF EPSCoR SEPHAS Fellowship, Aug. 2007 – Nov. 2008

Publications:
   Wenming Nie, Dongsheng Ma, Jiayong Pan, Jian Zhou, Kai Wu, 2006, $\delta^{13}$C Excursions of Phosphorite-bearing Rocks in Neoproterozoic-Early Cambrian Interval in Guizhou, South China: Implications for Palaeoceanic Evolutions: Journal of Nanjing University (Natural Sciences), 42 (3), 257-268

Thesis Title: Effects of Plant Uptake and Micro-topography on Chloride Transport in Arid Soils

Thesis Examination Committee:
   Chairperson, Dr. Zhongbo Yu, Ph.D.
   Co-Chair, Dr. Michael J. Nicholl, Ph.D.
   Co-Chair, Dr. Michael, H. Young, Ph.D.
   Committee Member, Dr. Wanda J. Taylor, Ph.D.
   Graduate Faculty Representative, Dr. Zhonghai Ding, Ph.D.