WATER FLOW THROUGH INDURATED CALCIC HORIZONS

IN ARID NEW MEXICO

By

Graciela Rodríguez-Marín

Independent Study Submitted in Partial Fulfillment of the Requirements

for the Degree of Master of Science in Hydrology

New Mexico Institute of Mining and Technology

Socorro, New Mexico

July 2001

ABSTRACT

Indurated stage IV calcic horizons are an important feature of many soils in New Mexico. Several previous studies have described the occurrence of dissolution pipes in these horizons but didn't quantify pipe frequency. In this study I test the hypothesis that surfaces with indurated calcic horizons have pipes exhibiting considerable downward water fluxes. First, the frequency of pipe occurrence is assessed from field data gathered along a 32 km trench, 2.2 m deep and 0.6 m wide, which had been excavated on the La Mesa surface for the placement of a gas pipe line. Thirteen to sixteen percent of the La Mesa surface is underlain by pipes with diameters from 0.4-22.0 m; this percentage is nearly one order of magnitude larger than any number previously reported in the literature. Inside the pipes the chloride concentrations in the soil water and the carbonate concentrations in the soil are approximately two orders of magnitude smaller than outside the pipes in the calcic horizons. This is strong evidence for the occurrence of considerable leaching through the pipes. My computer simulations of water fluxes through a representative pipe demonstrate not only that pipes do have a pronounced effect on downward water fluxes but also that the hydraulic characteristics of the soil filling and overlaying the pipes determine the magnitude of downward water fluxes through the pipe as well as through the calcic horizon. Estimated downward water fluxes at 300 cm depth through the pipes in fluvial and eolian soils were 3-20 and 24-95 mm per year, respectively. This compares to aerial fluxes of less than 0.03 mm per year in fluvial

soils and about 3 mm per year in eolian soils outside the pipes. Including the effect of pipe recharge in aerial recharge estimates increases the estimates from 0.03 to 0.1-0.8 mm per year in fluvial soils, and from 3 to 4-9 mm per year in eolian soils. The large difference between downward water fluxes outside and inside pipes, i.e. from less than 0.03 mm to 3-20 mm per year in the fluvial soil and from 3 mm to 24-95 mm per year in the eolian soil supports my research hypothesis that on surfaces with indurated calcic horizons in arid New Mexico locations with negligible downward water fluxes are intermixed with sites that have considerable downward water fluxes.

ACKNOWLEDGMENTS

I am grateful to my research advisor Dr. Bruce Harrison for his support and guidance during this research project. I want to thank the following persons who have contributed to this independent study either by assisting me with laboratory or field work or with the computer simulations Darrell Martin, Dr. Jan Hendrickx, Sung-ho Hong and Dr. Jirka Šimůnek at the George E. Brown Jr. U.S. Salinity Laboratory. I appreciate the critical comments by the members of my committee Dr. Peter Mozley and Dr. Robert Bowman. This study has been funded by the National Science Foundation (EAR-9903095).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 - INTRODUCTION

Ground water recharge is a critical component of the water balance in arid environments: it not only determines the sustainable yield of ground water aquifers but is also a key parameter for the evaluation of the vulnerability of those aquifers for contamination. For example, the southwestern deserts and rangelands are generally presumed to have extremely low ground water recharge rates and, therefore, are considered potentially suitable environments for the disposal of low- and high-level radioactive waste (Winograd, 1981).

Unfortunately, ground water recharge is controlled in such a complex manner by climate, soils, vegetation, and topography that it remains the least understood component of the hydrologic cycle in arid environments. Since arid climates are characterized by a mean annual potential evaporation that exceeds mean annual precipitation by an order of magnitude, many practitioners have assumed that ground water recharge through desert soils is negligible (Mann, 1976; Mercer *et al.*, 1983). On the other hand, it also has been recognized that the large spatial and temporal variability of precipitation in arid and semiarid regions will cause gross under-estimation of recharge when annually and areally averaged precipitation data are used in the calculations (e.g., Hendrickx and Walker, 1997; Lerner *et al.*, 1990). Gee & Hillel (1988) discuss this "fallacy of averaging" and point out that most of the recharge in arid regions is episodic, i.e. occurs during short time periods often on restricted areas.

Another characteristic of the arid regions in the southwestern United States is the formation of calcic soil horizons due to carbonate accumulation. Hennessy *et al.* (1983), Lattman (1977), and Phillips *et al.* (1988) have reported that calcic horizons generally have a low hydraulic conductivity and are an impediment for ground water recharge. Yet, Baumhardt and Lascano (1993) measured a saturated hydraulic conductivity of 75 cm/day in a calcic horizon and concluded that calcic horizons would not greatly impede vertical water movement. These contradictory findings may be explained by recognizing that a calcic horizon develops through different morphological stages which are characterized by different physical properties such as bulk density, thickness, cementation, and carbonate content (Gile *et al.*, 1966; Machette, 1985).

An increase in carbonate content causes a decrease of porosity and a reduction of permeability (Machette, 1985) and infiltration rates (Gile *et al.*, 1966). As a matter of fact, infiltration rates in calcic horizons appear inversely related to the carbonate content of these horizons (Gile, 1961). However, the implicit assumption that water flow and ground water recharge through indurated calcic horizons are essentially one-dimensional vertical processes without lateral components might have been the most critical oversight in previous hydrological studies addressing flow in calcic desert vadose zones. There is ample evidence of dissolution cavities and pipes in indurated calcic horizons in New Mexico, West Texas, and Arizona (e.g., Bretz and Horbert, 1949; Gile *et al.*, 1966; Gile and Hawley, 1966; Reeves, 1976). Pipes are defined as dissolution cavities that penetrate the calcic horizon completely and form conduits between the soil layers over- and underlaying it (Figures 1-1 and 1-2). No studies have been conducted to evaluate their hydrological implications. Gile *et al.* (1981) hypothesize that indurated calcic horizons surrounding pipes, due to their low hydraulic conductivity compared to the soil inside the pipe, deflect water into the pipes. Such lateral deflection may cause a considerable concentration of water towards the pipe resulting in preferential flow and increased depth of water penetration (e.g., Hendrickx and Flury, 2001).

The major goal of this study is to perform a quantitative analysis of water flow through indurated calcic horizons taking into account the possible effects of lateral flow. In order to place this study in its context, I will first present a literature review on ground water recharge mechanisms in arid environments as well as on the formation and characteristics of calcic horizons. Next, I will formulate a hypothesis concerning water flow processes through indurated calcic horizons.

Episodic Nature of Recharge Events

Several authors (Gee and Hillel, 1988; Hendrickx and Walker, 1997; Lerner *et al.*, 1990). have pointed out that most of the recharge in arid regions is episodic, i.e. occurs during relatively short time periods on often restricted areas. Since no data sets exist with a length of record covering thirty to one hundred years, computer simulations have been used for the evaluation of the episodic nature of recharge events. Rockhold *et al.* (1995) simulated a period of 30 years at the Hanford site in arid eastern Washington and found recharge rates to vary from 0.1 to 68.1 mm/year. Kearns and Hendrickx (1998) simulated

Figure 1-1. Typical pipes observed in Section One of the transect on the La Mesa surface.

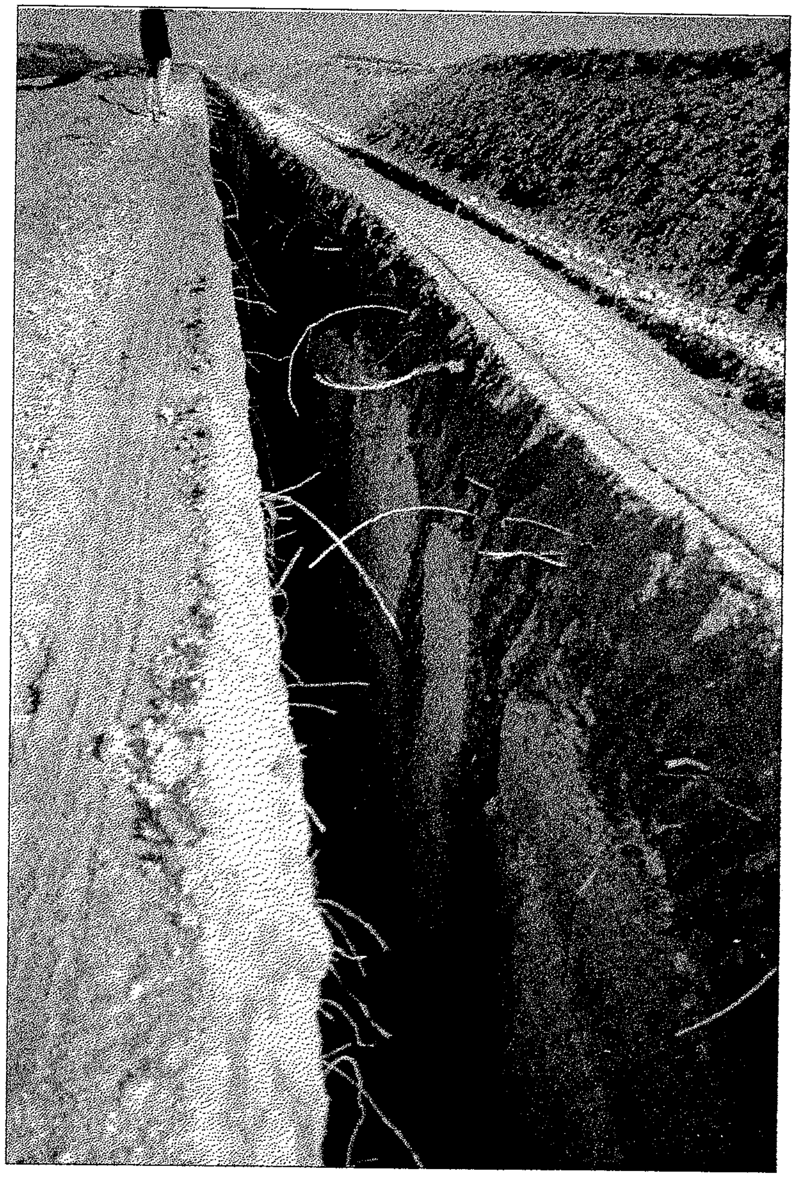
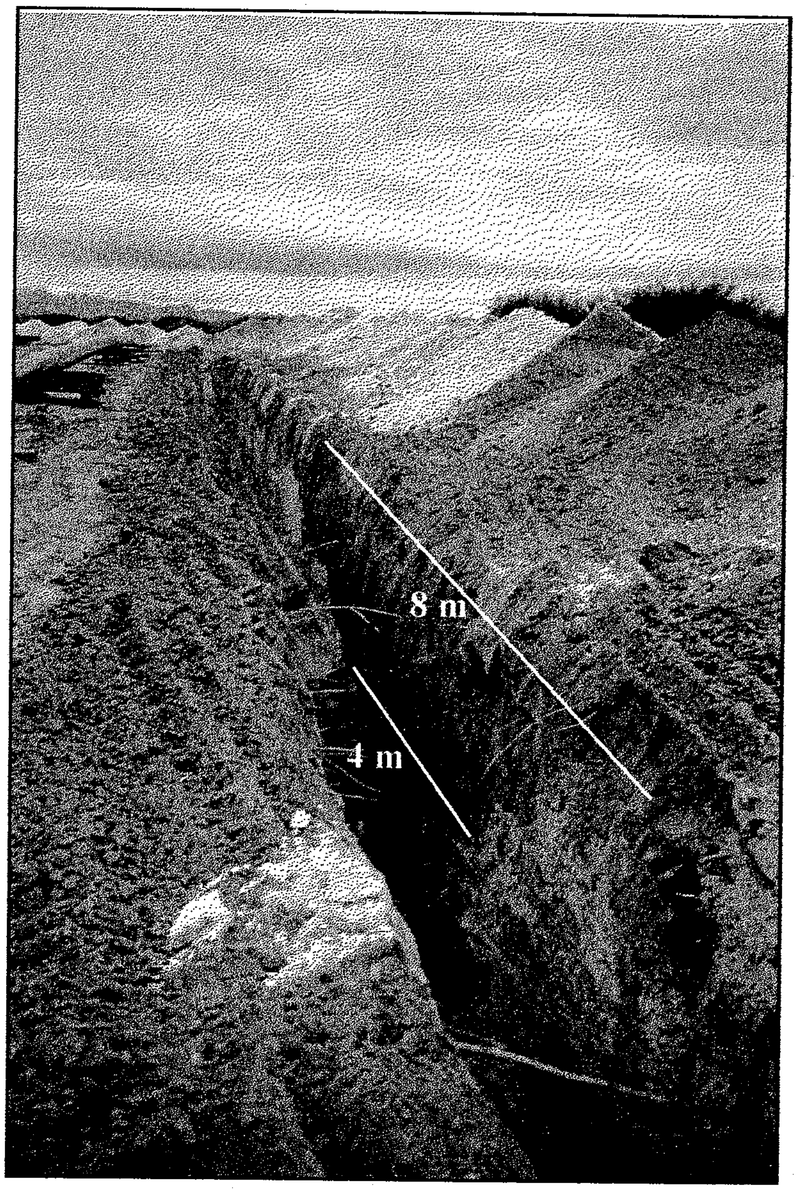


Figure 1-2. Typical pipe observed in Section Two of the trench on the La Mesa surface; top diameter is larger than bottom diameter.



ground water recharge in southern New Mexico using 100 years of daily precipitation data. They found that during the period 1890 to 1990, recharge events only occurred during five well defined periods varying in length from 3 to 7 years. Two of the five recharge events were initiated by the two largest single day precipitation events observed in the last century: 16.5 cm on August 30, 1935, and 10.4 cm on September 21, 1941. These two large single day events were followed by roughly average rainfall years. The three other recharge events were the result of several years in a row with above average rainfall while lacking any large, single day precipitation event.

The maximum percolation rates simulated by Kearns and Hendrickx (1998) at 2 m depth varied from 41.2 mm/year in a bare sand soil to 4.5 mm/year in a loam soil with grass cover while the mean rates varied, respectively, from 10.6 to 0.6 mm/year. The variable nature of individual recharge events as well as their rare occurrence demonstrate that recharge studies in arid environments should cover long time periods.

Effect of Soil Type and Vegetation on Recharge

Whereas daily calculations and long time periods show a great variation in recharge estimations compared to averaged periods, there are further complications when the role of soils and vegetation is included in recharge estimations. Lysimeter and field measurements provide convincing evidence that ground water recharge does occur in arid regions (e.g. Gee *et al.*, 1994; Stephens, 1994). For example, near Las Cruces, New Mexico, in a 6 m deep and 2.4 m diameter lysimeter filled with loamy fine sand and kept vegetation free, Wierenga & Jones (1995, *pers. comm.*) measured an average annual recharge rate of approximately 50 mm/year or about 20% of the mean annual precipitation of 250 mm/year during the period 1989-1994 . In Hanford (Washington), vegetation free lysimeters filled with coarse sand produced recharge rates approximating 15 to 55% of the annual precipitation of 160 mm/year while those filled with silt loam produced only limited recharge (Gee *et al.*, 1994). These lysimeter data are proof that precipitation recharge can occur in arid regions.

The amount of stored water that can be removed by vegetation depends mainly on the rooting depth. Shallow rooted grasses will remove less water than deeper rooted shrubs and trees. Eastham *et al.* (1993) found that soil water depletions were greater for trees than for pasture on a deep loamy sand. Soil water content measurements to 5 m depth showed that no water was extracted below 3.5 m under pasture, while under trees water content changes occurred from 0 to 5 m depth. Allison *et al.* (1990) compiled data to compare recharge rates under mallee communities comprising of several species of *Eucaluptus* before and after clearing. Recharge rates under the original native mallee vegetation were less than 0.1 mm/year. After clearing the land was revegetated with agricultural crops and pasture which have shallower rooting depths than the *Eucaluptus* trees. As a result, recharge rates after clearing increased by almost two orders of magnitude to between 5 and 30 mm/year.

The interaction between vegetation and soil type is complicated, so numerical computer models are frequently used to evaluate their effects on recharge. The simulation study by Rockhold *et al.* (1995) at the Hanford site in arid eastern Washington clearly demonstrates the effect of soil type and vegetation on recharge rates (Table 1-1).

Table 1-1. Predicted recharge rates for different soil and vegetation types for the period 1963-1993 at the Hanford Site (Rockhold *et al.*, 1995).

	Recharge Rate (mm/year)											
Soil Type	No Vegetation			Cheatgrass			Bunchgrass			Sagebrush		
	avg	min	max	avg	min	max	avg	min	max	avg	min	max
Sand	22.0	10.5	68.1	15.7	7.0	45.5	5.4	1.5	14.9	0.5	0.2	1.5
Silt Loam	7.6	4.9	10.7	5.8	3.7	8.2	2.8	1.7	6.4	1.0	0.4	4.4
Silt Loam/ Sand	1.5	1.0	2.0	1.2	0.8	1.9	0.6	0.3	1.6	0.2	0.1	0.8

Although a bare soil always results in more recharge, the absolute differences in recharge between a bare and vegetated soil become less when the soil texture becomes finer. The annual recharge rate on silt loam soil for Sagebrush vegetation is twice that on sand with similar vegetation. This unexpected difference is the result of the different hydraulic properties for the two soils; silt loam has a higher hydraulic conductivity at low water contents than sand so that more water can percolate deeper into the profile.

Recharge Hypotheses in Arid Vadose Zones

Although the lysimeter and field measurements support the hypothesis that ground water recharge in arid regions may be common, other data contradict this viewpoint. High concentrations of conservative solutes, such as chloride, in the root zone (but lower concentrations below the root zone), enrichment of stable isotopes in the near-surface zone (but less enrichment deeper), and generally water potential gradients that result in upward flow in the top 5 to 10 meters (Phillips, 1994) lead to the hypothesis that, at present, desert vadose zones are hydrologically very stable and experience negligible recharge.

These two contradictory hypotheses (some recharge vs. no recharge) may be reconciled by recognizing different recharge mechanisms: (i) direct or diffuse recharge resulting from widespread infiltration of rain water at the point of impact; (ii) localized recharge where some horizontal flow occurs into local depressions resulting in focused infiltration; (iii) water flow through preferential pathways (Hendrickx and Flury, 2001). Hendrickx and Walker (1997) present a number of case studies demonstrating the occurrence of these mechanism in arid environments. Scanlon (1992) demonstrated the existence of preferred pathway flow through fissured sediments in the Chihuahuan desert of Texas. Water fluxes calculated from vertical chloride profiles in these sediments ranged from 1 to 8 mm/year and were as much as 350 times higher than those calculated for adjacent ephemeral stream sediments. In Australia, Johnston (1987) demonstrated the simultaneous occurrence of capillary and macropore flow within the same soil mass without the presence of clearly defined macropores. Over most of his 700 m^2 experimental area recharge rates varied from 2.2 to 7.2 mm/year, while a small portion of the site had rates between 50 to 100 mm/year.

These two case studies are proof that locations with negligible recharge and sites with considerable recharge rates can exist side-by-side in arid environments. Depending on the sampling location one can find support for either one of the hypotheses stated previously. Since preferential pathway flow and localized recharge almost always are associated with a lateral flow component (German, 1990; Hendrickx and Flury, 2001), they will occur on only a fraction of the total area. This may explain why evidence in support of the hypothesis of negligible recharge is more abundant than that in support of the recharge hypothesis.

Recharge Mechanisms through Indurated Calcic Horizons

This study focuses on the recharge mechanisms that operate in environments with indurated calcic horizons which have been formed by accumulation of calcium carbonates. In most arid environments the principal source of calcium carbonate in soils is airborne calcium carbonate (a component of eolian dust) and Ca^{++} dissolved in rainwater (Gile *et al.*, 1981; Machette, 1985). This material enters the soil with infiltrating rain water so that over time there is calcium carbonate accumulation in the soil. Shreve and Mallery (1932) observed calcium carbonate -which they refer to as *caliche*- to occur in hard layers or in somewhat softer amorphous masses. They suggested there is a need for a comparative study of the different types of calcium carbonate hardpans. More than thirty years later Gile *et al.* (1966) described two distinct sequences of carbonate morphology with four stages associated with increasing age (Table 1-2). In soils that contain little gravel, carbonate is precipitated as filaments which later coalesce to form nodules. In gravelly soils, initial precipitation is around the individual clasts that become completely coated with carbonate with time. With continued carbonate accumulation most of the soil pores and other openings become filled with carbonate resulting in the formation of the plugged horizon in the last part of stage IV and a significant decrease in infiltration rate. After formation of the plugged horizon, a laminar carbonate precipitate develops at the top of the calcic horizon. It is believed to form from water perched on the top of the calcic horizon; the carbonate is precipitated when the water evaporates. The perched water tends to occur in small hollows and irregularities at the top of the calcic horizon, eventually filling these with laminar carbonate deposits. Ultimately, the surface irregularities are filled in and a relatively smooth, low permeability surface results that enhances lateral flow of water which may predominate over vertical movement through the horizon. At this stage, the calcic horizon is growing upwards to the surface, engulfing the overlying argillic horizon. Thus, the zone of

Table 1-2. Four stages of carbonate accumulation in two morphological sequences (Gile *et al.*, 1981).

Stage and General Character	Diagnostic Carbonate Morphology	
	Gravelly Sequence	Nongravelly Sequence
I		
Weakest expression of macroscopic carbonate	Thin, discontinuous pebble coatings	Few filaments or faint coatings
II		
Carbonate segregations separated by low-carbonate material	Continuous pebble coatings, some interpebble fillings	Few to common nodules
III		
Carbonate essentially continuous; plugged horizon forms in last part	Many interpebble fillings	Many nodules and internodular fillings
IV		
Laminar horizon develops	Laminar horizon overlying plugged horizon	Laminar horizon overlying plugged horizon

reduced hydraulic conductivity is closer to the surface in older soils.

Bachman and Machette (1977) and Machette (1985) have defined six stages of calcic horizon development (Table 1-3). Up until stage IV the pattern of carbonate precipitation differs depending on the parent material. By stage IV laminar carbonate is being precipitated at the top of the calcic horizon. Since after stage IV the calcic horizon is much closer to the soil surface the next two stages are thought to be the result of extensive reworking of the calcic horizon from surficial geomorphic processes including burrowing by animals, cracking by roots, frost and salt shattering. Stage V calcic horizons have thick laminar layers and pisolithic structures while stage VI horizons are characterized by multiple episodes of brecciation and pisolith formation. In this study I will use the classification by Bachman and Machette (1977) presented in Table 1-3.

In the arid areas of New Mexico, stage V and VI horizons are thought to develop over millions of years (Gile *et al.*, 1981). The development of calcic horizons is accompanied by increases in the bulk density and decreases in porosity and permeability (Machette 1985). The bulk density of late Pleistocene calcic horizons (stage III) is about 1.8 g/cm^3 whereas that of the laminar layer on a stage IV calcic horizon is about 2.2 g/cm^3.

Another feature of the stage IV calcic horizons is the development of pipes through the horizon. Pipes are usually only found in soils that are late Pleistocene in age or older. As will be discussed in Chapter 2 of this study, the pipes range in width from a few decimeters to ten meters or more and are usually wider on older surfaces. Laminar carbonate layers are frequently found lining the edges of pipes. Dating these laminar

Table 1-3. Six stages in the morphological sequence of carbonate deposition (Bachman and Machette, 1977).

Stage	Diagnostic Carbonate Morphology
I	Filaments or faint coatings. Thin, discontinuous coatings on lower surface of pebbles.
II	Firm carbonate nodules, few to common but isolated from one another. Matrix may include friable interstitial accumulations of carbonate. Pebble coatings continuous.
III	Coalesced nodules in disseminated carbonate matrix.
IV	Platy, massive indurated matrix. Relict nodules may be visible in places. Plugged. May have weak incipient laminae in upper surface. Case hardening common on vertical exposures.
V	Platy to tabular, dense and firmly cemented. Well developed laminar layer on upper surface. May have scattered incipient pisoliths in laminar zone. Case hardening common.
VI	Massive, multilaminar and brecciated, with pisoliths common. Case hardening common.

layers indicated that they were formed during the late Pleistocene approximately 20,000 years BP (Gile *et al.*, 1981). Evidence has been presented by Gile *et al.* (1981) that water moves on top of the plugged indurated calcic horizon laterally toward the pipes. The different soil water regimes within and outside pipes results in different soils forming on the same aged surface since the soil in the pipe is more strongly leached and has much less carbonate in the profile than the soil between the pipes (Gile *et al.*,1981).

Study Objective

In this study I test the hypothesis that surfaces with indurated calcic horizons have areas exhibiting considerable downward water fluxes. The hypothesis is based on area-wide observations of dissolution pipes in the indurated calcic horizons of arid New Mexico (Bachman and Machette, 1977; Bretz and Horbert, 1949; Gile *et al.*, 1966; Gile and Hawley, 1966) which may play a significant role in the recharge process.

The remainder of this study is organized into four major sections. Chapter 2 deals with the frequency of occurrence of pipes in calcic horizons. If only a small fraction of the surface is underlain by pipes, their effect on the overall downward water flux will remain limited. If, however, a major part of the surface is occupied by pipes, then they may play an important role in the recharge process. Chapter 3 provides a description of our field and laboratory measurements. In Chapter 4, data from Chapters 2 and 3 are used to model water flow through indurated calcic horizons in order to evaluate their effect on recharge and to test the hypothesis that on surfaces with indurated calcic horizons in arid New Mexico locations with negligible downward water fluxes are intermixed with sites that have considerable downward water fluxes. Finally, Chapter 5 summarizes the conclusions of this study and outlines my future research plans.

2 - OCCURRENCE OF PIPES IN INDURATED CALCIC HORIZONS

In arid regions worldwide, investigators have observed the occurrence of pipes in calcic horizons. Bretz and Horbert (1949) reported solution cavities in calcic horizons on the Mescalero Plain (New Mexico) and broad funnel-shaped pipes on the Llano Estacado (New Mexico). Gile et al. (1966) and Bachman and Machette (1977) described thick calcic horizons on the La Mesa surface (New Mexico) that are penetrated by funnel-shaped pipes. Gile and Hawley (1966) found pipes through calcic horizons on alluvial fans at the southern end of the Jornada del Muerto basin (New Mexico). Johnson (1997) observed large and small pipes in the southern Tularosa Basin and Otero Mesa in southern New Mexico. McGrath (1984), Osterkamp and Wood (1987), and Reeves (1976) reported that pipes are common in the Ogallala and Blackwater Draw Formations on the Llano Estacado in Texas. Shreve and Mallery (1932) studied *caliche* within a 320 km radius of Tucson in Arizona. Although they didn't refer directly to pipes, they did report that the lateral extent of *caliche* layers is "extremely variable, and the continuity of the surface is frequently broken." Knox (1977) observed pipes around Saldanha Bay (South Africa) in caliche profiles with calcretes that are similar to those described by Bretz and Horbert (1949) in New Mexico.

There are different hypotheses regarding the formation of pipes through indurated calcic horizons. The most widely known hypothesis postulates that the pipes have been formed during Pleistocene pluvials as a result of dissolution processes along fractures, animal burrows, or cavities created when large roots decay (Gile *et al.*, 1981). Another hypothesis postulates that the pipes are formed by animals digging through the calcic horizon (Johnson 1997). Dating of the laminar layers covering the sides of many pipes yields evidence that they have formed during the late Pleistocene. After their formation they have been exposed to atmospheric conditions and have been filled with young materials like fluvial and eolian deposits. Indeed, large fluvial fans with complex channel patterns have formed on the La Mesa surfaces during the late Pleistocene and the Holocene (Love and Seager, 1996). In the fluvial deposits I have observed weakly developed calcic horizons. Finally, eolian sands covered the older surfaces.

Pipe diameters vary greatly. Gile and Hawley (1966) measured an average width of 0.4 m with a minimum and maximum of 0.2 and 0.6 m. Bretz and Horbert (1949) observed pipes with diameters of several meters, whereas Gile et al. (1981) report diameters from a few centimeters to ten meters or more. The latter authors found a correlation between pipe diameter and soil age; the widest and most complex pipes are found in the oldest soils. Although most references indicate that pipes are a common feature in well developed calcic horizons, only Gile and Hawley (1966) have measured the frequency of pipe occurrence. They surveyed a 150 m long transect in an area where pipes are relatively numerous and counted 11 pipes with an average width of 0.4 m. The distance between the pipes varied from 3 to 18 m. They calculated that the pipes covered about two percent of the measured transect. Pipe depths vary from about a meter to several meters (Gile et al., 1981; Reeves, 1976).

Field observations and laboratory analyses reported in the literature strongly indicate that individual pipes act as conduits for water flow. Soils in pipes contain less exchangeable sodium than surrounding soils due to more frequent deep wetting (Gile et al., 1981). Gile et al. (1966, 1981) argue that the sequence and age of the carbonate accumulations within and outside pipes suggest that pipes "must have been regularly flushed by water". Gile and Hawley (1966) observed reddish, high-chroma clay that may be traced downward from some pipes and spreads out or slightly penetrates the underlying paleosol. Osterkamp and Wood (1987) have made similar observations in the upper Ogallala Formation. Where excavations expose beds beneath organic-rich playa deposits, it is common to encounter a zone with white leached sand. Below this sand layer, cemented zones of iron and manganese oxides are common. The leached sandy zones are an indication for transport of reduced forms of these metals dissolved in recharge water that flows downward through solution pipes. Gile et al. (1981) hypothesize that the laminar and plugged calcic horizons surrounding pipes, due to their low hydraulic conductivity compared to the sand soil inside the pipe, deflect water into the pipes. Such a lateral deflection will cause a concentration of water towards the pipe resulting in a preferential flow process and increased depths of water penetration (Hendrickx and Flury, 2001).

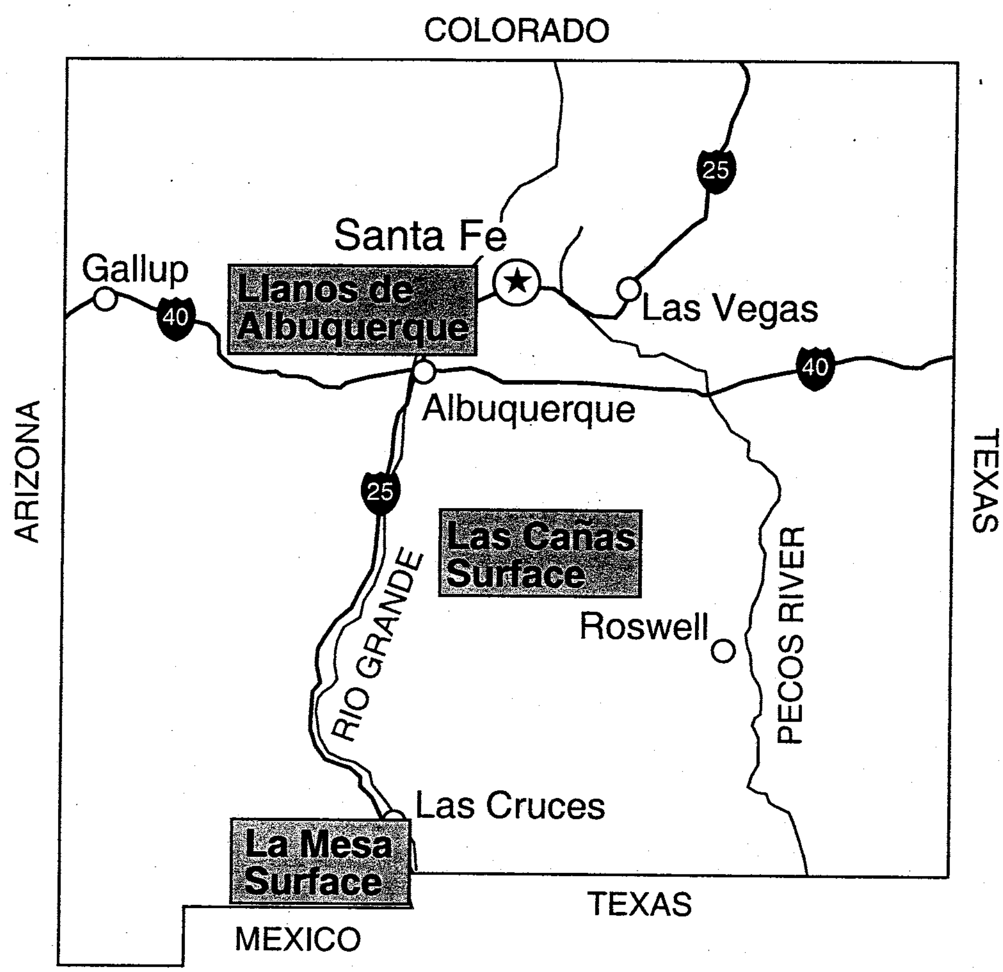
Hendrickx and Walker (1997) discuss the importance of localized ground water recharge for the water balance of arid regions. They review a number of field investigations (e.g. Meyboom, 1966; Wood and Sanford, 1995) and modeling studies (Boers, 1994; Kearns and Hendrickx, 1998; Nieber et al., 1993) that demonstrate how accumulation of water in small surface depressions after large precipitation events may cause a large increase in downward water fluxes. However, it seems unlikely that preferential water flow through pipes can impact the regional water balance if they only cover two percent of the area as measured by Gile and Hawley (1966). Unfortunately, due to their concealed subsoil location, it is very difficult to investigate pipe occurrence, which explains why so few data have been reported in the literature. Therefore, the objective of this Chapter is to investigate the frequency of pipe occurrence in indurated calcic horizons.

2-1 METHODS AND MATERIALS

Field observations of pipe occurrence have been made at several sites in the Rio Grande Basin of New Mexico. From south to north the sites are: the Potrillo Maar near the U.S.-Mexico boundary west of El Paso on the Upper La Mesa surface, the Lower La Mesa surface southwest of Las Cruces, the Las Cañas Surface northeast of Socorro, and the Llano de Albuquerque west of the city of Albuquerque (Figure 2-1).

In this study, I focus on the Upper and Lower La Mesa surfaces, which have developed on the axial Rio Grande deposits that mainly consist of sands and gravels. The surface was abandoned by the Rio Grande during the early-middle Pleistocene. Since that time, a calcic soil with an indurated calcic horizon has formed. The Upper La Mesa is a constructional surface that has developed on sands and pebbly sands of the Camp Rice Formation fluvial facies (Gile *et al.*, 1981). The east, west, and south boundary scarps

Figure 2-1. Locations in New Mexico where I have observed pipes in indurated calcic horizons.



seem to be fault scarps along which the surface has been lifted. Erosional modifications occurred much early than deposition of the surficial gravel and sand of the lower La Mesa surface. Tectonic displacement has continued episodically into the late Quaternary (Gile *et al.*, 1981), so calcic horizons may have been exposed sometime during this period. The present ground water table is at least 100 m deep. The vegetation consists mainly of snakeweed, mesquite, and *Yucca elata*. Diagnostic features of the soils on this surface are the argillic and petrocalcic horizons. Petrocalcic Paleargids are dominant in the areas where the calcic horizon occurs whereas Typic Haplargids are found in pipes. (Gile *et al.*, 1981). The Paleargids are characterized by a thick stage IV-V carbonate horizon with multiple laminar horizons while the Haplargids in the pipes are characterized by a thick Bt horizon and a stage II carbonate horizon (Gile *et al.*, 1981). The Lower La Mesa is a relict basin-floor surface with generally non-calcareous or slightly calcareous parent sediments. Coppice dunes occur over most of the Upper and Lower La Mesa surfaces. Vegetation is mostly confined to the dunes and consists of mesquite and occasionally four-wing saltbush. Many areas between the dunes are barren. The water table is 90-100 m below the surface. Typic Torripsamments are found in the dune area while Haplargids are in the areas between the dunes. The Haplargids are characterized by an argillic horizon with some macroscopic carbonate and a thick, stage III-IV petrocalcic horizon at depths ranging from 1 to 1.5 m. Laminar horizons do occur in places (Gile *et al.*, 1981).

The data presented in this chapter come from a 32 km trench, 2.2 m deep and 0.6 m wide, which had been excavated on the La Mesa surface for the placement of a gas pipe line. Since the trench was almost immediately backfilled I only could survey two sections in detail: Section One with length 4 km and Section Two with length 6 km. In each of these sections the following information was recorded: the depth of the calcic horizon, the number of pipes, the diameter of each pipe (measured at the top of the calcic horizon as well as at the bottom of the trench), and the distance between pipes..

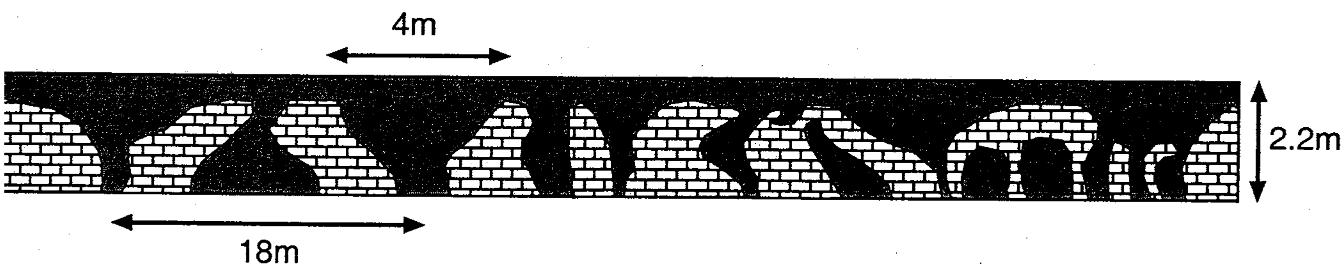
2.2 RESULTS AND DISCUSSION

2.2.1 Description of Pipes and Terminology

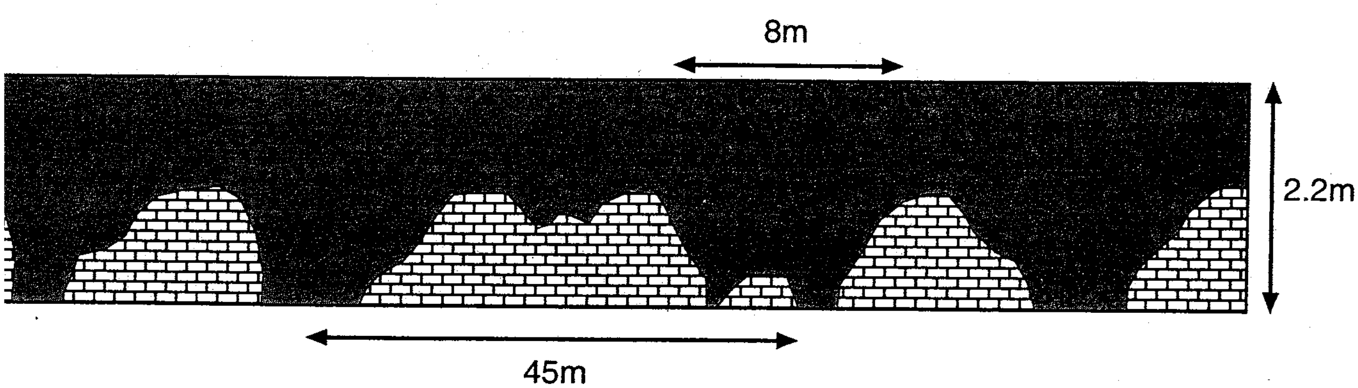
The field survey of Sections One and Two of the trench on the La Mesa surface revealed the presence of a large number of pipes of different shapes and sizes (Figure 2-2). The features of the two sections are quite different. The depth of the calcic horizon in Section One is less than 0.65 m whereas in Section Two it is 1.2 to 1.5 m. The overlying sediments in Section One are all eolian sands whereas in Section Two the sediments are either of fluvial or eolian origin. In Section One, no carbonate accumulation was found inside the pipes whereas in Section Two Stage I and II calcic horizons have been observed indicating that the eolian filling is more recent than the fluvial. Furthermore this indicates that the stages IV - VI calcic horizons were at one time exposed to the atmosphere. In Section One there are indications of present day dissolution: (i) the calcic horizon surface is often quite soft; (ii) the yellow to light brown color in the top 10 cm of the calcic horizon is an indication of accumulation of fine soil particles and suggests seepage of water through this layer; (iii) at some locations the calcic horizon has broken

Figure 2-2. Pipe shapes in Sections One and Two of the trench on the La Mesa surface. Pipe distances and diameters are not to scale.

Section One



Section Two



up into blocks that are found in the underlying soil; (iv) many dissolution spaces in the calcic horizon resemble karstification features (Figure 1-1). In both sections, laminar layers have been observed covering the calcic horizon inside as well as outside of the pipes (Figure 2-3).

Figure 2-4 presents schematics of the two different pipe types that I have observed in the field. It also contains the terms that will be used in this study to describe the different aspects of the pipe such as the filling material and the overlying units. In addition, I introduce four different deep percolation fluxes that will be discussed in detail in Chapter 4. I recognize the downward flux through the pipe itself, $q_{inside\ pipe}$, the downward flux through the calcic horizon outside of the pipe, $q_{outside\ pipe}$, and the overall downward flux in the area, $q_{with\ pipe}$, which represents the areally averaged downward flux. Not shown in the figure is the downward flux that would occur in an area without pipes, $q_{without\ pipe}$, since this is an hypothetical flux on the LaMesa Surface. It will be equal or close to $q_{outside\ pipe}$.

2.2.2 Pipe Dimensions

Reports in the literature (Bachman and Machette, 1977; Bretz and Horbert, 1949; Gile *et al.*, 1966; Gile and Hawley, 1966) and our field observations (Figure 2-2) indicate a wide variety of pipe shapes and diameters. Yet there are similarities. A typical pipe can be characterized by a top diameter that often is slightly larger than its bottom diameter (Figure 1-2). For example, in Sections One and Two the average top diameters of the pipes are 4.2 and 8.5 m, respectively, while the average bottom diameters are 2.9 and 4.5

Figure 2-3. Detail of laminar layer that has frequently been observed to cover the calcic horizons in Section Two of the transect on the La Mesa Surface.

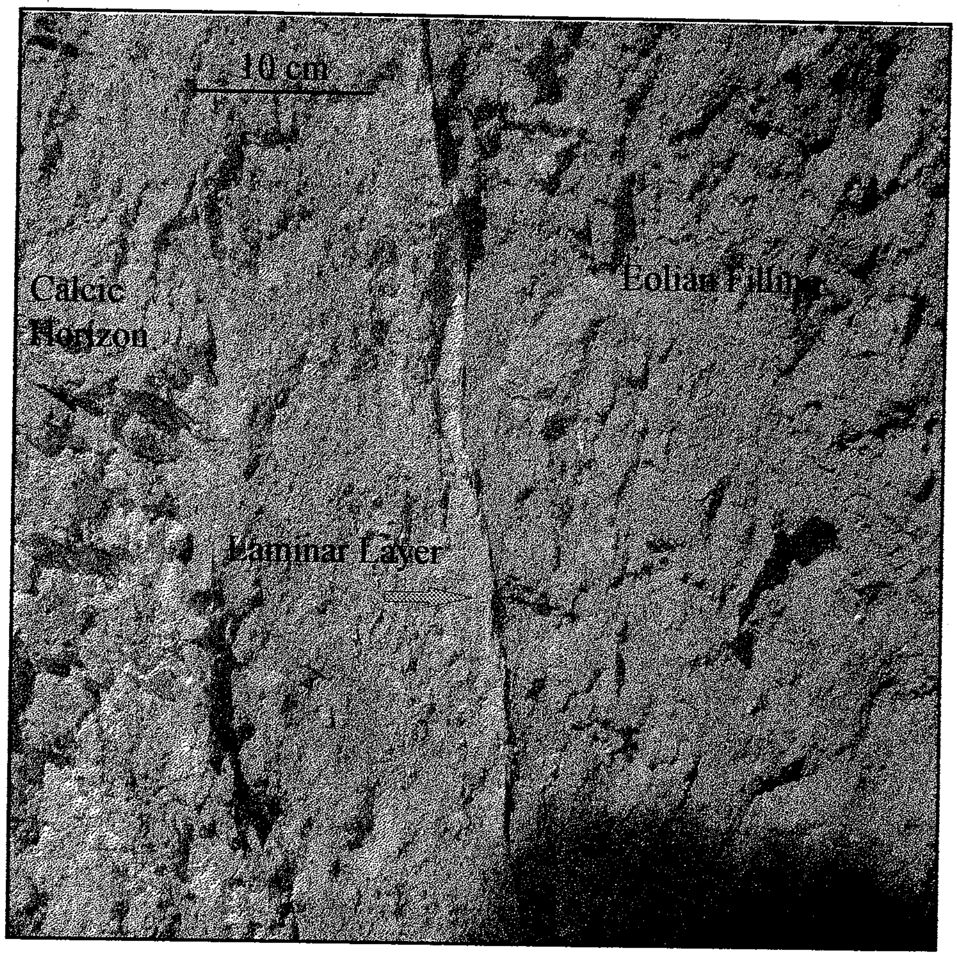
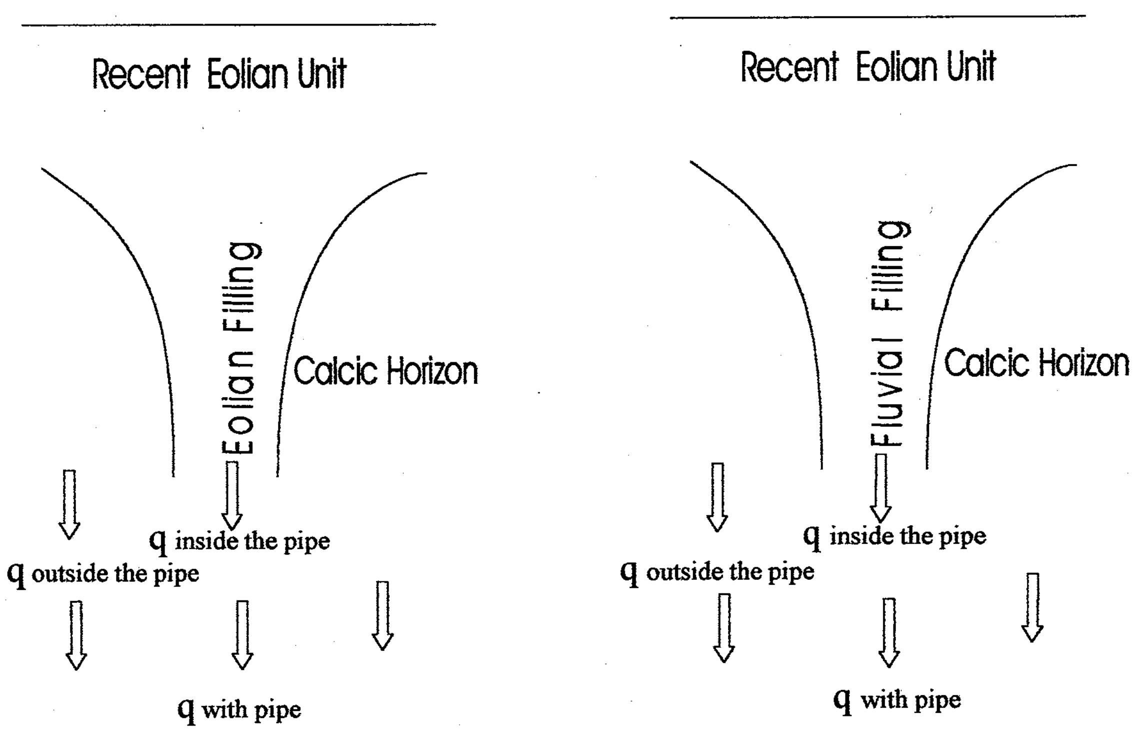


Figure 2-4. Schematic presentation of a pipe with eolian and a pipe with fluvial filling.



m. However, in Section One, some pipes tend to have more of a hourglass shape: narrowing from top to center, widening from center to bottom of the pipe (Figure 2-5).

Figures 2-6 and 2-7 present pipe top diameters and pipe distances observed along Sections One and Two. The pipe diameters are quite variable and range from approximately 1-15 m in Section One and from 2-21 m in Section Two. The average pipe top diameter in Section Two is twice that of Section One, but the standard deviations are 3.7 m for both sections (Table 2-1). The coefficient of variation decreases from 88% in Section One to 44% in Section Two, indicating that the larger pipes in Section Two have less variation in their diameter than the smaller pipes in Section One.

I have evaluated the frequency distributions of the pipe diameters (Figure 2-8). None of the distributions was normal and no transformation of the pipe diameters yielded an approximately normal distribution. Therefore, I performed a nonparametric test on the ranks of the diameters (Conover and Iman, 1981). Such a test reveals whether the median diameters of Section One (8.7 m) and Two (3.0 m) are significantly different. The *t*-test gave a significant difference at the 0.01 probability level. Therefore, it can be concluded that the two sections have indeed completely different pipe diameters.

2.2.3 Pipe Distance

The average distance between pipes (from edge to edge) in Sections One and Two is, respectively, 22 and 58 m. The respective standard deviations and coefficients of variation are 33 and 54 m and 149 % and 93 % (Table 2-1). Thus, the larger pipes in Section Two have less variation in their diameter than the smaller pipes in Section One.

Figure 2-5. Typical pipe shape observed in Section One of the trench on the La Mesa surface; the top and bottom diameter have similar dimensions while the pipe shows a constriction in its middle section.

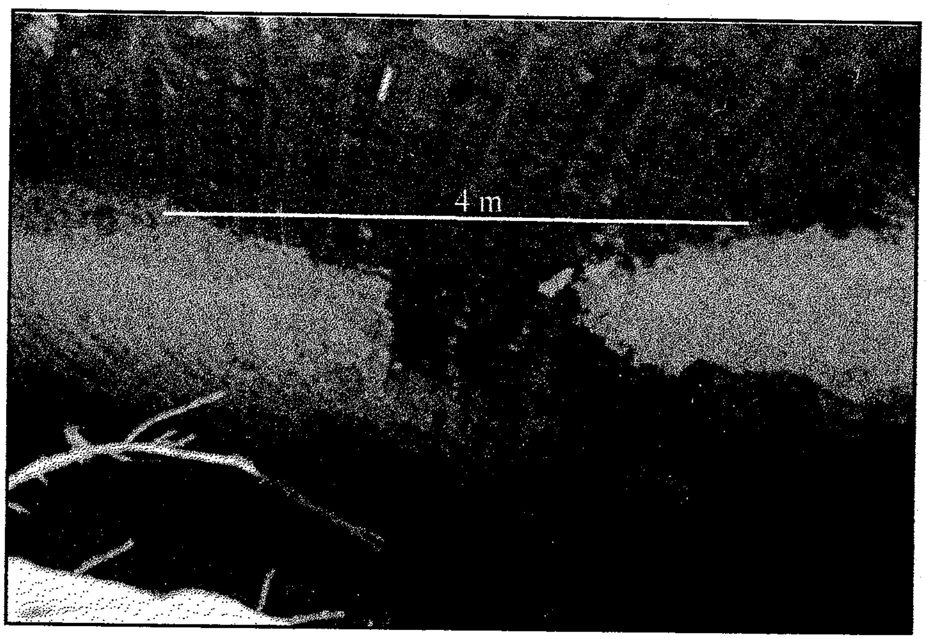


Figure 2-6. Pipe distance (edge to edge) and pipe top diameter along Section One.

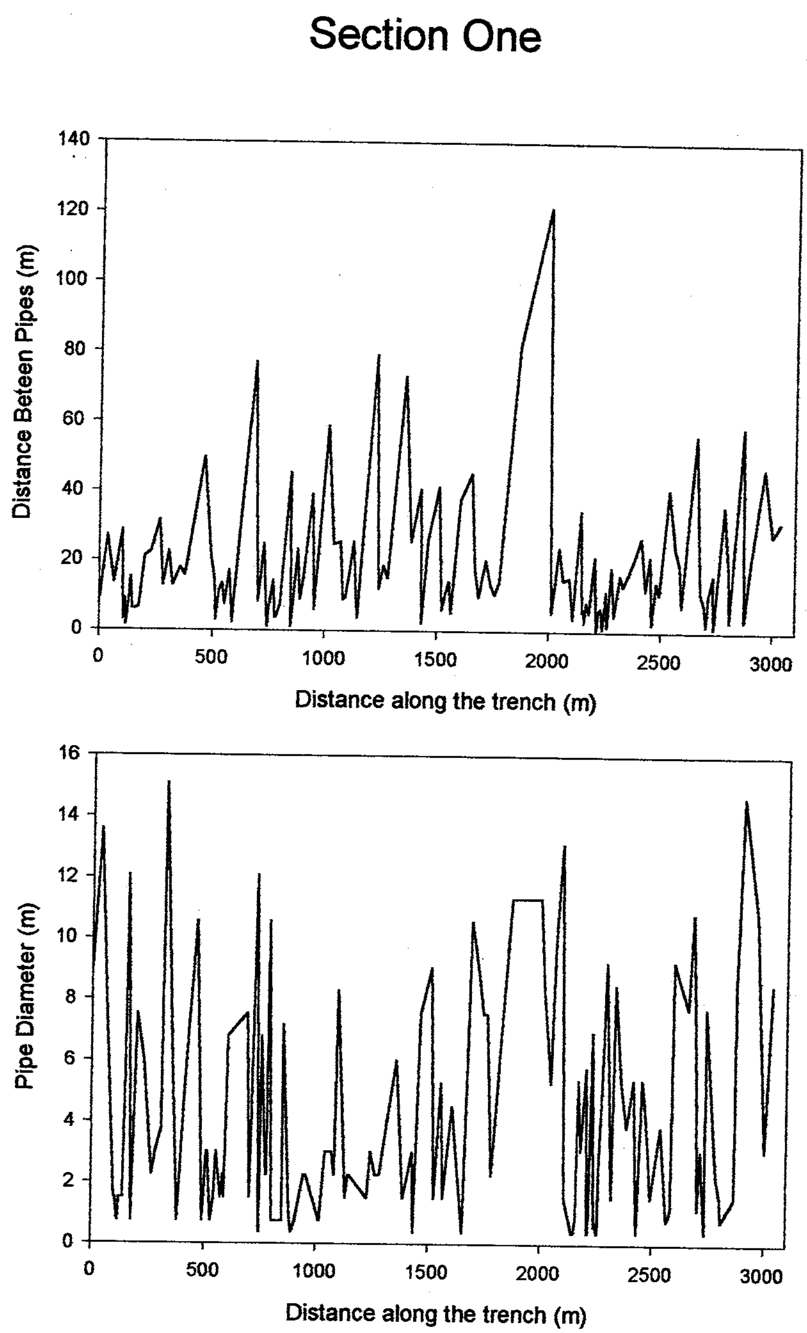


Figure 2-7. Pipe distance (edge to edge) and pipe top diameter along Section Two.

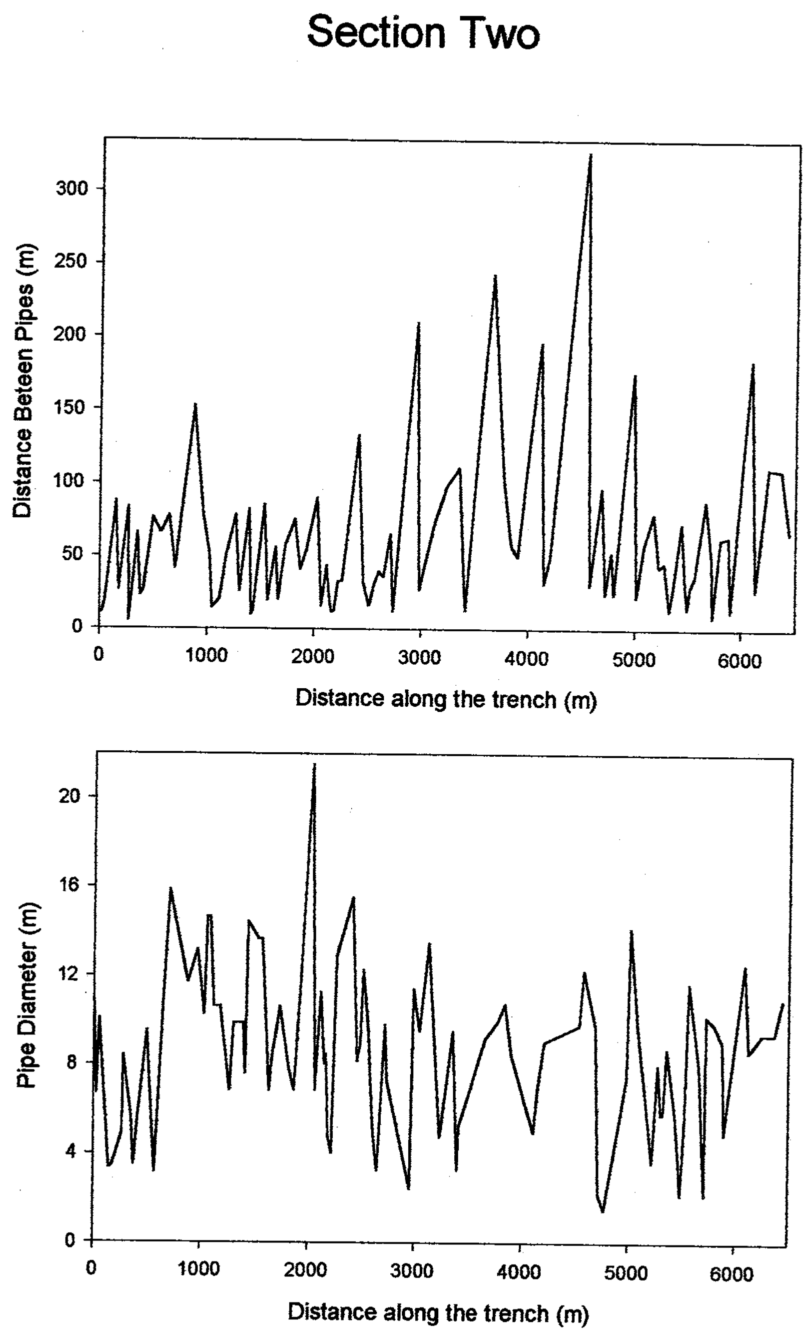
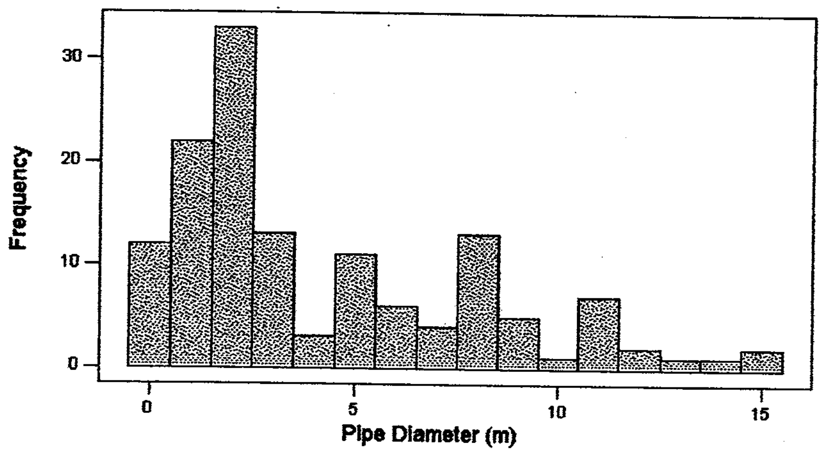


Table 2-1. Descriptive statistics of pipe diameters and distances in Sections One and Two on the La Mesa surface.

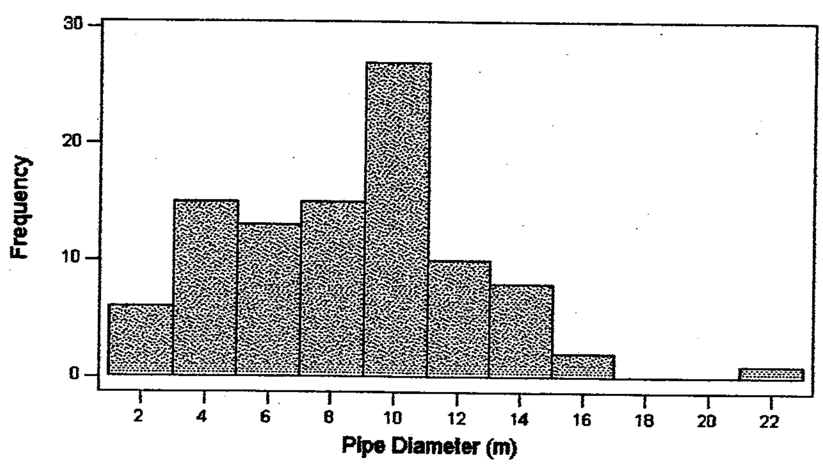
	Section One			Section Two		
Length of Section	3790 m			6441 m		
Number of Observations	143			96		
Parameter	Mean (m)	Std. Dev. (m)	Coef. Var. (%)	Mean (m)	Std. Dev. (m)	Coef. Var. (%)
Top Diameter	4.2	3.7	88	8.5	3.7	44
Bottom Diameter	2.9	2.6	92	4.5	2.9	64
Distance	22	33	149	58	54	93

Figure 2-8. The frequency distributions of the pipe diameters in Sections One and Two.

Section One



Section Two



Again, a *t*-test reveals that the pipe distance of both sections is significantly different at the 0.01 level. Also, the variability of the pipe diameter in Section One is clearly larger than that in Section Two.

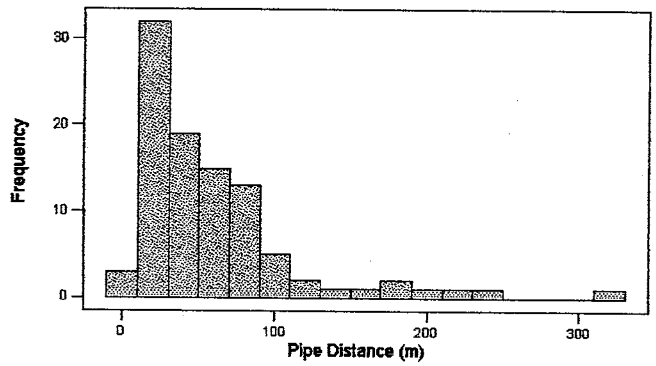
I have evaluated the frequency distributions of the pipe distances (Figures 2-9). None of the distributions was normal but a log-transform of the distances yielded an approximately normal distribution (Figure 2-10). A *t*-test on the log-transformed distances gave a significant difference at the 0.01 probability level. Therefore, it can be concluded that the two sections have completely different pipe distances.

I have also checked if a correlation exists between pipe diameter and distance by plotting these two variables against each other (Figure 2-11). The cloud of points on this figure demonstrates that pipe diameter and distance are not correlated to each other.

Using the average pipe diameters and distances the percentage of the total surface area covered by pipes is calculated as $4.2/(22+4.2)\times100=16\%$ for Section One and $8.5/(58+8.5)\times100=13\%$ for Section Two. These percentages are six to eight times larger than the two percent previously reported by Gile and Hawley (1966). One reason for this discrepancy may be that their area of investigation at the southern end of the Jornada del Muerto basin, New Mexico, is different from the La Mesa surface. They report pipe distances between 3-20 m and pipe diameters from 0.25-0.6 m; the former not unlike the distances found in this study, the latter somewhat smaller. Another reason may be that they only surveyed a transect of 150 m on which they found 11 pipes. This number of pipes is much smaller than the 233 pipes used in this study to derive pipe statistics. The large fraction of the La Mesa surface underlain by pipes is a strong indication that pipes

Figure 2-9. The frequency distributions of the pipe distances in Sections One and Two.

Section One



Section Two

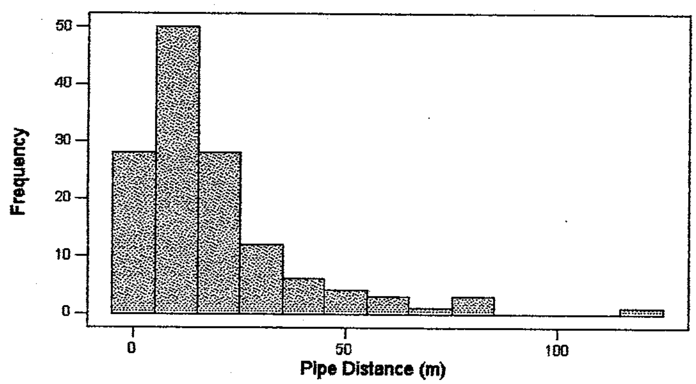
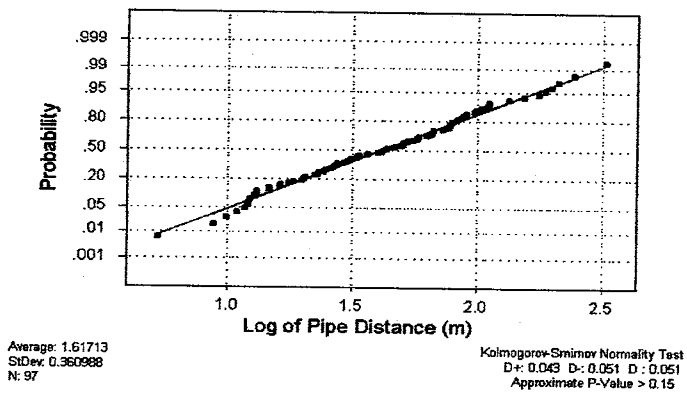


Figure 2-10. The Kolmogorov-Smirnov normality test for the log-transformed pipe distances of Sections One and Two.

Section One



Section Two

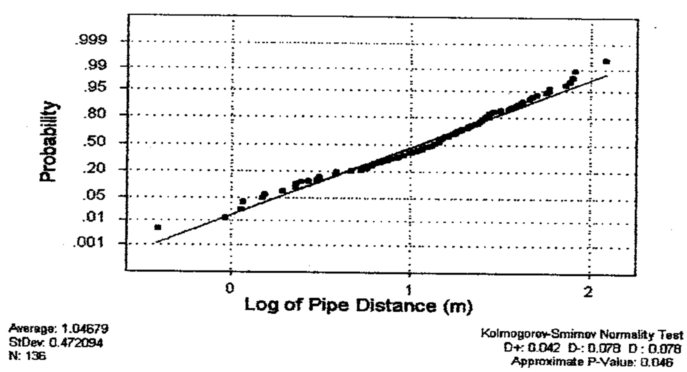
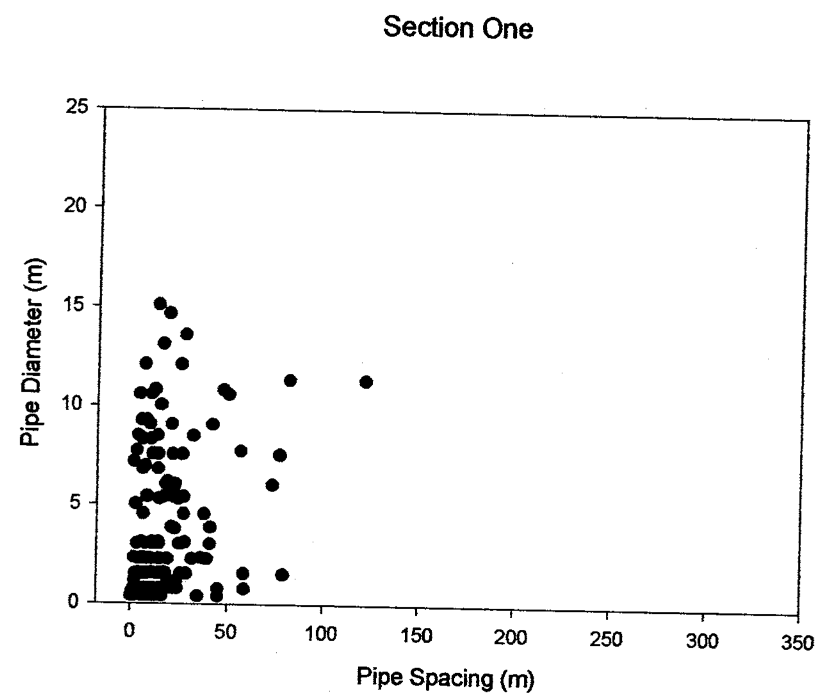
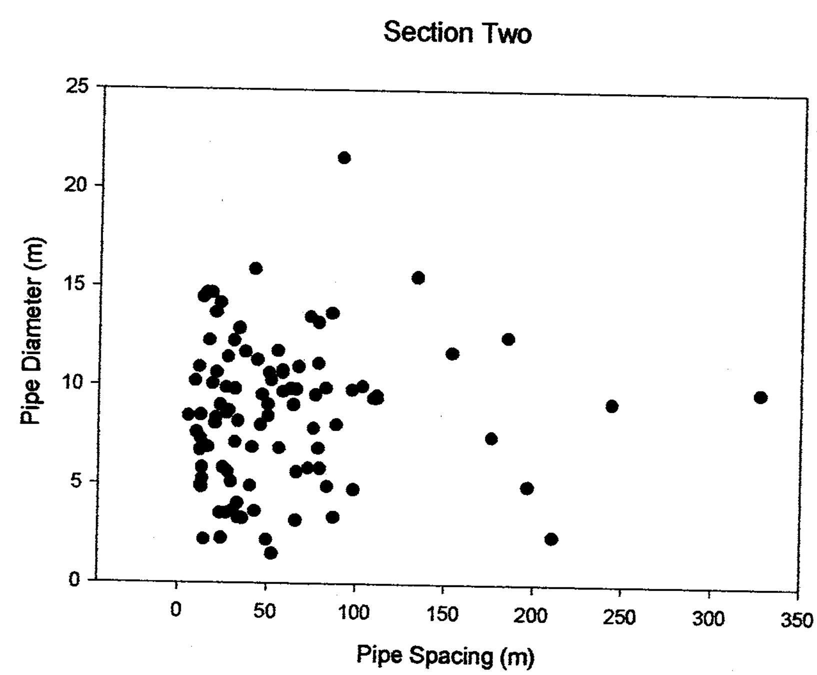


Figure 2-11 Plots of pipe distance versus pipe diameter for Sections One and Two.





will affect downward water fluxes and, therefore, may play an important role in the water balance of this arid region. This will be further investigated in Chapters 3 and 4 of this report.

3 - PHYSICAL CHARACTERIZATION OF SOIL PROFILES WITHIN AND OUTSIDE PIPES

For a thorough understanding of the effect of pipes on water flow through desert vadose zones it is necessary to investigate the physical characteristics of the soil profiles within and outside the pipes. Gile *et al.* (1981) described soil profiles within and outside pipes as, respectively, Typic Haplargid and Petrocalcic Paleargid which demonstrates the different nature of soil development within and outside pipes.

Several authors have discussed the change in soil texture and physical properties as calcium carbonate accumulates. Calcium carbonate bonds to clay and silt particles, causing highly aggregated clay soils to behave as coarse sands (Francis and Aguilar, 1995). Stakman and Bishay (1976) measured physical properties of highly indurated calcic horizons from marine lacustrine soils in Egypt. They found that calcium carbonate causes an increase in bulk density and a decrease in porosity and soil water content over the whole range of soil water pressures. Baumhardt and Lascano (1993) analyzed samples from an indurated calcic horizon overlying the Ogallala aquifer in Texas and found a change in texture from clay to sandy loam after removal of the carbonates.

The few studies that have measured the hydrological properties of calcic horizons yielded contradictory results. Lattman (1977) reported that calcic horizons are impermeable to water, whereas Hennessy *et al.* (1983) showed that caliche nodules (calcium carbonate nodules) could adsorb up to 25 % by weight of water but that no water would pass through the caliche layer. Phillips *et al.* (1988) studied ^{36}Cl distributions in an arid soil and also concluded that calcic horizons have a very low permeability for water. On the other hand, Baumhardt and Lascano (1993) measured the saturated vertical hydraulic conductivity of a calcic horizon at 75 cm/day and concluded that calcic horizons would not greatly impede vertical water movement. Unfortunately, none of these hydrological studies clearly characterized the age or stage of development of the calcic horizon and therefore it is difficult to compare the results or to make generalizations about the hydraulic characteristics of these horizons. One exception is the work by Shreve and Mallery (1932) who recognized two different kinds of calcium carbonate (*caliche*) in soils: hard stratified layers and softer amorphous masses with a higher porosity. After immersion in water for 48 hours the "hard" and "soft" *caliche* contained, respectively, 3.0-6.4 and 12.0-17.3 weight percent water. Capillary rise and evaporation experiments show a clear difference in water conducting properties of the "hard" and "soft" *caliche.* Although these experiments were done well before Bachman and Machette (1977) proposed their classification system, they are strong evidence of a correlation between the development stage of a calcium carbonate horizon and its hydraulic properties.

The principal objective of this chapter is the characterization of those soil parameters that either affect current water flow or reflect past water flow patterns through a calcic horizon. The physical soil properties that were evaluated are soil texture, carbonate content, chloride content, and gravimetric water content. In addition, hydraulic soil properties of pipe fillings and calcic horizons on the La Mesa surface were determined using laboratory measurements and literature data.

3.1 METHODS AND MATERIALS

Twelve soil profiles in two pipes were sampled on the La Mesa surface in southern New Mexico (Figure 2-1). In addition, I took volumetric soil samples at one other location. All sampling locations are located along the gas pipe line (Figure 3-1). The two pipes were different: one with a fluvial filling and one with an eolian filling. At Pipe One with fluvial filling four profiles were sampled within the pipe and four outside the pipe; at Pipe Two with eolian filling two profiles were taken within the pipe and two outside the pipe. The samples along each vertical profile were taken to a depth of about 2.4 m at 0.2 m intervals starting at the soil surface, i.e. 0, 20, 40, 60, ..., 220, 240 cm. The gravimetric samples were analyzed for gravimetric soil water content, chloride and carbonate content, and soil texture using standard procedures (Singer and Janitzky, 1986).

Two undisturbed volumetric soil samples were taken in the fluvial filling and two in the eolian filling for determination of the saturated hydraulic conductivity and the soil water retention curve. The sample columns were made of transparent plexy glass with a diameter and length of 0.15 and 0.23 m, respectively, which yields a sample volume of 4064 cm^3 (Figure 3-2). The inside of the sample columns was covered with grease to decrease soil resistance during sampling and to prevent leakage of water during the

Figure 3-1. Locations of samples taken along the gas pipe line on the La Mesa surface.

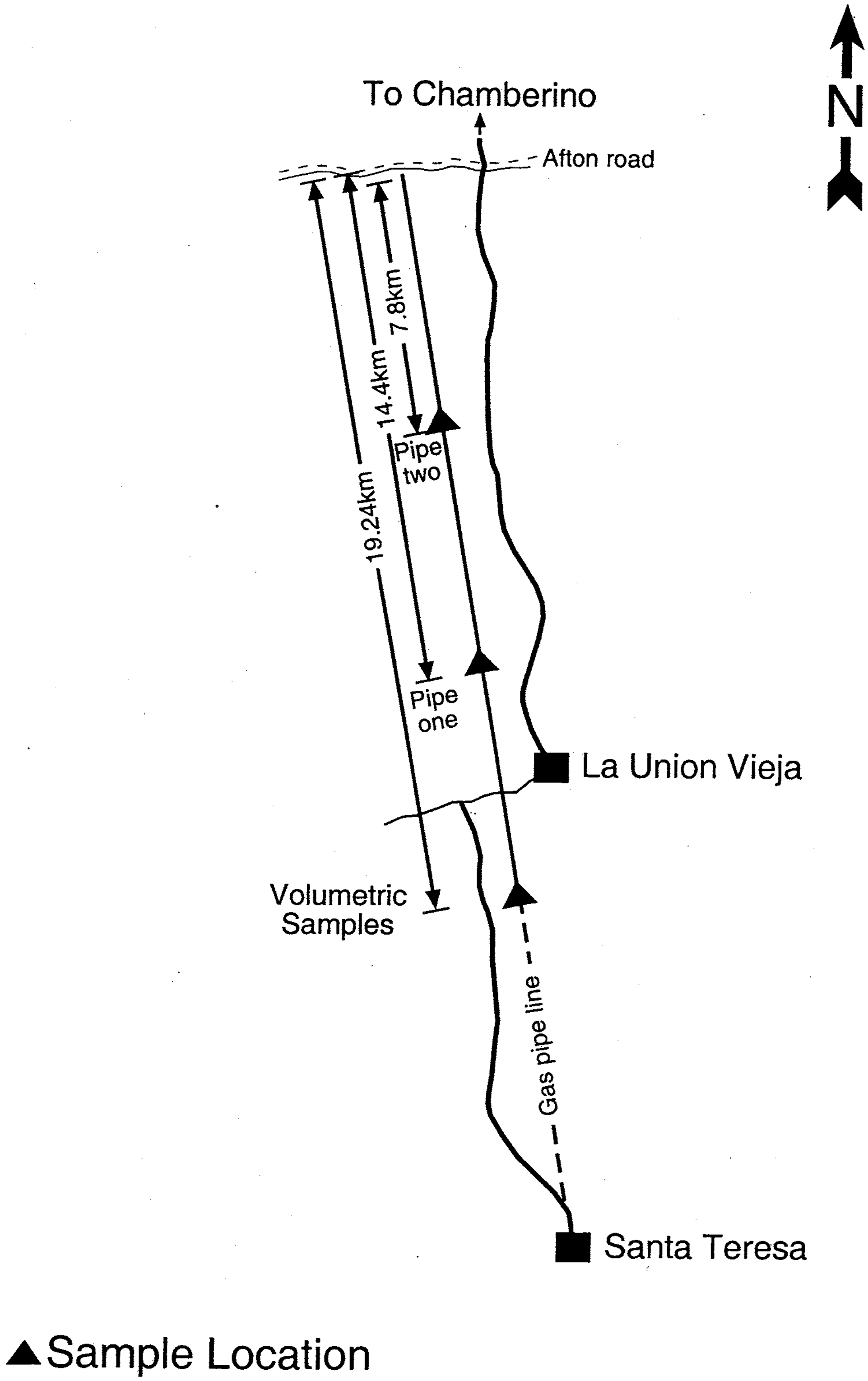
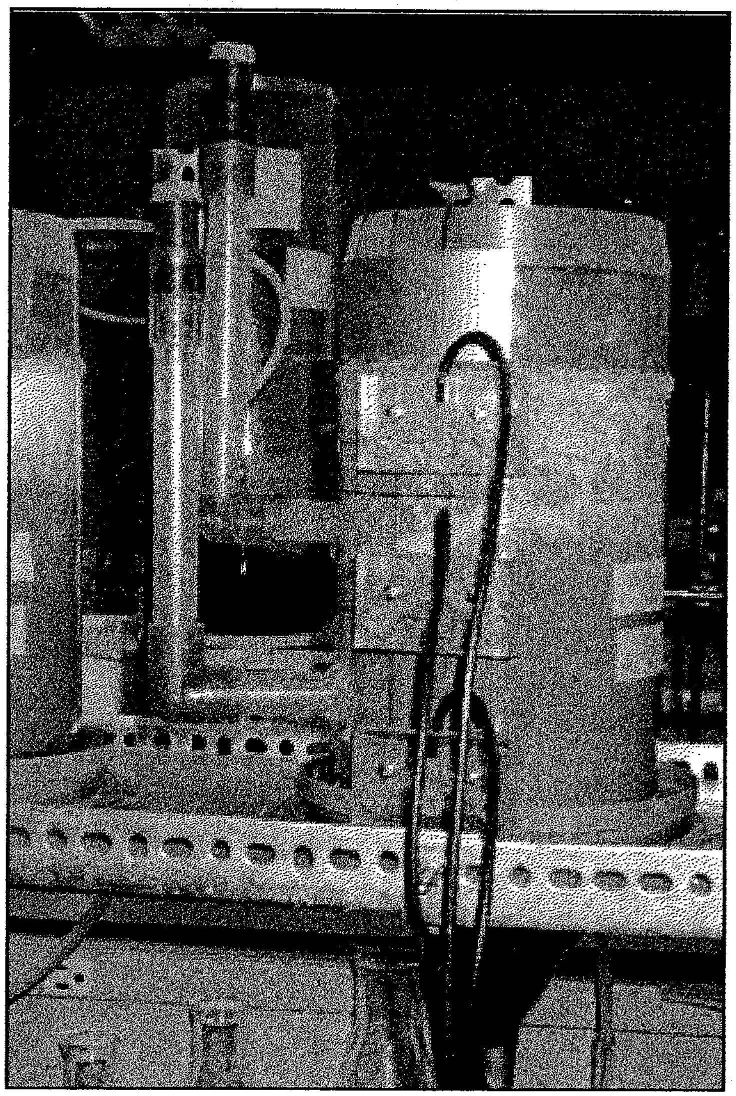


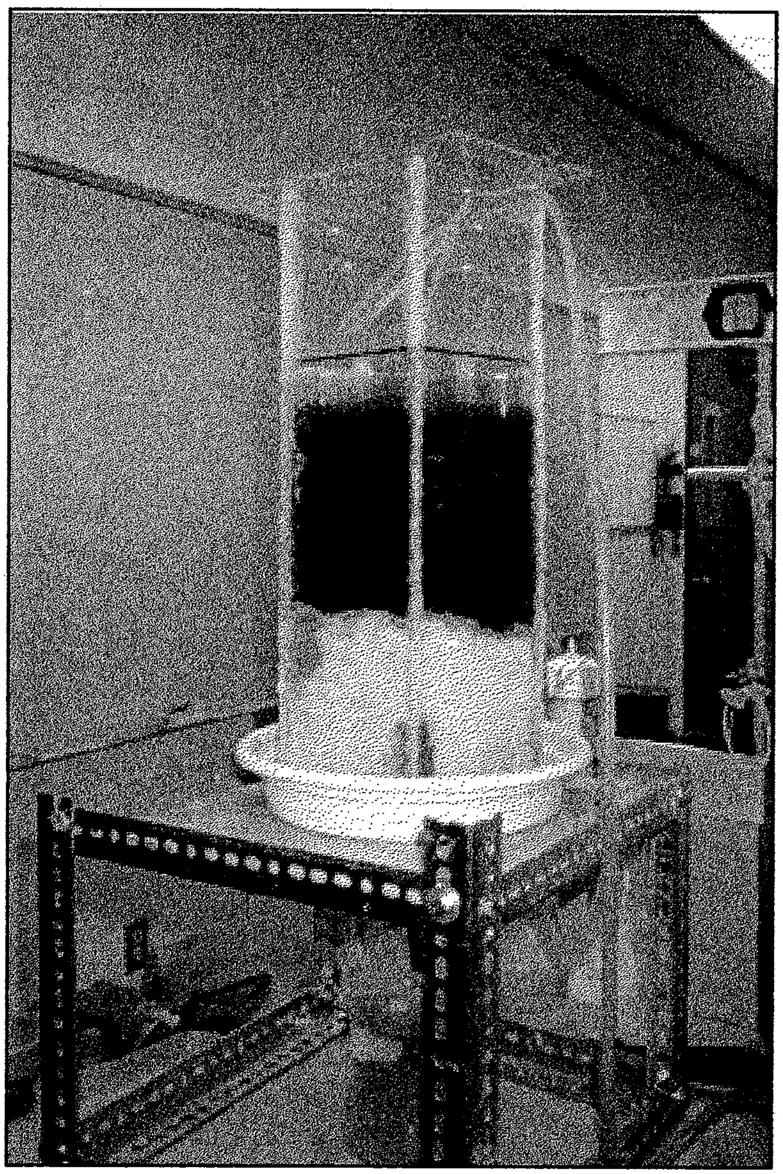
Figure 3-2. Experimental setup for measurement of the saturated hydraulic conductivity and soil water retention in the volumetric soil samples. Two tensiometers have been inserted at the side of the column to measure soil water pressures. Three TDR probes have been inserted into the front of the column to measure volumetric soil water contents.



measurement of the saturated hydraulic conductivity. The columns were pushed into the soil by hand and by light tapping with a rubber hammer while removing the surrounding soil. The saturated hydraulic conductivity was measured with the constant head method (Klute and Dirksen, 1986). The soil water retention curve was measured by simultaneous measurements of soil water content and soil water pressure during the drying of the volumetric sample (Figure 3-2). At depths 5, 10, and 15 cm a time domain reflectometry probe was inserted to measure volumetric soil water content (e.g. Hendrickx 1990). At depths 10 and 20 cm a tensiometer was installed to measure soil water pressure using a tensimeter (Hendrickx 1990; Marthaler *et al.* 1983). The measurements were used to obtain the van Genuchten parameters with a nonlinear curve fitting routine of the spreadsheet Excel.

At the Potrillos Maar a large piece of indurated calcic horizon was gathered in the field. After shaping this piece into a cube using a rock saw, four plastic walls were glued around it to permit measurement of the saturated hydraulic conductivity (Figure 3-3). After measuring the saturated hydraulic conductivity a color dye was applied to the water to indicate flow paths through the calcic horizon sample. This sample was collected about 15 km to the South of the trench but its indurated calcic material was found to be quite similar to the indurated calcic horizon encountered in the trench.

Figure 3-3. Experimental setup for measurement of the saturated hydraulic conductivity in an indurated calcic horizon sample. The color dye has been applied for detection of fracture flow. The water depth above the sample is 20 cm.



3.2 RESULTS AND DISCUSSION

3.2.1 Soil Texture and Carbonate Content

Table 3-1 presents the particle size distribution with depth within and outside the two pipes. The soil texture in the calcic horizon varies from sandy loam to sandy clay loam at Pipe One and from loamy sand to sandy clay loam at pipe Two. The filling material within Pipe One (fluvial filling) varies from sandy loam to sand and within Pipe Two (eolian filling) from loamy sand to sand. Thus, the soil texture at Pipe Two tends to be a little coarser than Pipe One. Also, the soil texture in the calcic horizons is finer than the overlying soil and the soil within the pipes. This is a result of illuviation of clay particles together with the calcium carbonate during the formation of the calcic horizons.

Table 3-2 presents the distribution of carbonate content with depth within and outside the two pipes. The depth of the calcic horizon is 1 m at Pipe One and 0.6 m at Pipe Two. Comparing the carbonate contents measured in the pipe and in the calcic horizon, a large increase is observed. In Pipe One (fluvial filling) carbonate content increases from 1-11 to 9-50% and in Pipe Two (eolian filling) from 0.3-17 to 22-54%. The highest values in the fillings of Pipe One are found at depth 0-0.4 m where an horizontal accumulation of carbonate was observed in the field. In Pipe Two the highest values are observed at depth 0.2-0.4 m close to the edge of the pipe.

Our data are similar to those gathered by Gile *et al.* (1981) in the same area of the La Mesa surface. Due to the great differences in soil profiles within and outside pipes they classified the soil within the pipes as, respectively, Typic Haplargid and Petrocalcic Paleargid which demonstrates the different nature of soil development.

Table 3-1. Soil texture distribution with depth at Pipe One (fluvial filling) and Pipe Two (eolian filling).

Depth (cm)	Pipe One Fluvial Filling								Pipe Two Eolian Filling			
	Profile Number								Profile Number			
	P1	P2	P3	P4	P5	P6	P7	P8	P1	P2	P3	P4
0 - 20	LS	SL	SL	LS	LS	LS	S	LS	S	LS	S	LS
20 - 40	LS	SL	SL	SL	SL	SL	LS	LS	S	LS	LS	LS
40 - 60	S		LS	SL	LS		LS	LS	S	LS	LS	LS
60 - 80	SL		LS	SL	LS	LS	LS	LS	LS	LS	LS	LS
80 - 100			LS	LS	LS	LS	LS		LS	LS	LS	LS
100 - 120	LS		LS	LS	LS	S	SL	SL	LS	LS	LS	LS
120 - 140	SCL	SCL	LS	LS	LS	LS	LS	SL	SL	LS	LS	
140 - 160	SCL	SCL	LS	LS	LS	SL		SL	SL	LS	LS	LS
160 - 180	SL	SCL	LS	LS	LS		LS	SL	SCL	S	LS	SL
180 - 200	SL	SL	LS	LS	S	S					LS	SL
200 - 220				LS	SL	S	SL					

S Sand
LS Loamy Sand
SL Sandy Loam
SCL Sandy Clay Loam

Calcic Horizon

Table 3-2. Carbonate content (%) distribution with depth at Pipe One (fluvial filling) and Pipe Two (eolian filling).

Depth (cm)	Pipe One Fluvial Filling								Pipe Two Eolian Filling			
	P1	P2	P3	P4	P5	P6	P7	P8	P1	P2	P3	P4
0 - 20	6.4	6.6	4.3	5.1	4.6	5.0	3.3	3.1	4.4	0.7	0.3	0.5
20 - 40	5.0	6.9	7.8	6.7	6.5	5.1	5.4	4.7	6.4	4.4	16.7	1.8
40 - 60	6.3	3.9	3.8	3.0	1.5	3.5	3.0	3.6	5.4	5.7	2.2	2.0
60 - 80	3.9	4.1	1.3	1.4	3.7	2.2	2.2	1.5	37.8	2.7	1.0	5.5
80 - 100	10.6	3.9	1.5	1.0	1.8	0.8	1.4	2.0	38.0	1.8	5.9	7.5
100 - 120	38.9	28.9	0.9	0.8	2.9	0.8	1.5	18.0	43.6	1.4	4.0	8.7
120 - 140	9.0	33.6	1.1	1.2	2.7	1.3	1.3	29.6	37.0	1.3	1.7	14.6
140 - 160	41.8	50.9	3.8	0.8	1.5	1.5	1.8	34.6	26.0	2.3	3.7	14.2
160 - 180	40.1	47.5	3.0	0.7	1.6	1.2	2.1	50.2	53.8	1.8	2.3	22.1
180 - 200	26.4	28.8	0.6	0.7	1.5	1.6	26.1	45.1			10	35.6
200 - 220				0.8	1.6	1.4	40.8				19	

Calcic Horizon

3.2.2 Gravimetric Water Content

Table 3-3 presents the distribution of gravimetric water content with depth within and outside the two pipes. Although the data only present a "snapshot in time" taken in October 1998 after two rainy days, they do reveal some interesting features. The amount of water retained in the calcic horizon is about two to three times more than that inside the pipe. This is to be expected since the finer texture of the calcic horizon is more suitable to retain water at the negative soil water pressures that are common to desert soils.

In Pipe One the wetting front did not penetrate below depth 0.6 m as is indicated by the sudden decrease in water content from around 8 percent in the top layer to around 3 percent deeper in the profile. In Pipe Two the water contents are much more homogeneous throughout the profile. As a matter of fact I have observed during sampling that the wetting front penetrated this profile to at least a depth of 2 m. This difference in depth of wetting through the fluvial and eolian pipe fillings can be explained by the difference in hydraulic conductivities measured in the laboratory (see Section 3.2.4 below).

3.2.3 Chloride Content

Table 3-4 presents the distribution of chloride concentration in the soil solution with depth within and outside the two pipes. Maximum chloride concentrations were found in the indurated calcic horizons with values 36-260 mg/L in Pipe One and 0.2-90 mg/L in Pipe Two. The pipe fillings have values 1-110 mg/L in Pipe One and 0.4-7.4

Table 3-3. Gravimetric water content (%) distribution with depth at Pipe One (fluvial filling) and Pipe Two (eolian filling).

Depth (cm)	Pipe One Fluvial Filling								Pipe Two Eolian Filling			
	P1	P2	P3	P4	P5	P6	P7	P8	P1	P2	P3	P4
0 - 20	7.8	8.0	7.8	8.0	7.9	8.5	6.5	6.0	6.6	5.2	5.2	6.0
20 - 40	3.5	5.7	5.1	7.3	8.2	8.1	6.0	3.7	7.8	7.0	6.1	5.6
40 - 60	3.6	3.6	2.7	2.7	3.1	5.3	2.7	3.2	8.0	7.8	5.9	6.0
60 - 80	4.0	4.8	2.3	2.3	2.4	2.3	2.5	3.6	10.4	5.7	8.3	20.4
80 - 100	4.7	5.3	2.6	2.1	2.3	2.2	2.5	4.2	10.1	5.0	7.3	9.1
100 - 120	7.4	7.8	2.8	2.2	2.6	2.0	2.8	5.9	9.5	4.2	6.9	8.7
120 - 140	9.8	9.1	3.2	2.5	2.7	2.1	2.6	6.7	9.6	3.9	6.6	9.6
140 - 160	8.7	9.4	3.3	2.4	2.2	2.4	2.7	6.7	10.5	4.2	5.8	9.0
160 - 180	9.0	10.1	3.2	2.4	2.7	2.5	2.8	8.5	11.9	4.7	6.0	8.2
180 - 200	10.1	10.4	2.9	2.5	2.8	2.5	11.4	8.5	11.9	4.7	7.7	9.3
200 - 220				2.5	3.4	2.4	9.1	9.1				

Calcic Horizon

Table 3-4. Chloride content (ppm) distribution with depth at Pipe One (fluvial filling) and Pipe Two (eolian filling).

Depth (cm)	Pipe One Fluvial Filling								Pipe Two Eolian Filling			
	P1	P2	P3	P4	P5	P6	P7	P8	P1	P2	P3	P4
0 - 20	1.0	7.5	3.7	8.9	2.4		10.0	39.0	0.5	9.8	13.0	12.0
20 - 40	16.0	68.0	17.0	13.0	12.0	12.0	15.0	46.0	0.4	1.5	9.9	8.2
40 - 60	17.0	58.0	13.0	11.0	5.8	13.0	13.0	56.0	0.5	1.3	9.3	7.8
60 - 80	39.0	82.0	13.0	5.2	2.7	12.0	11.0	31.0	0.2	1.7	8.7	7.6
80 - 100	68.0	110.0	35.0	14.0	10.0	12.0	17.0	54.0	12.0	1.8	8.1	7.7
100 - 120	140.0	190.0	30.0	13.0	17.0	14.0	28.0	78.0	30.0	2.2	8.7	8.9
120 - 140	40.0	210.0	33.0	22.0	29.0	24.0	25.0	110.0	110.0	1.9	9.7	14.0
140 - 160	36.0	160.0	39.0	26.0	43.0	31.0	27.0	130.0	59.0	2.6	9.6	20.0
160 - 180	260.0	200.0	41.0	21.0	32.0	30.0	23.0	220.0	90.0	3.2	14.0	38.0
180 - 200	240.0	190.0	40.0	24.0	46.0	27.0	76.0	100.0			17.0	28.0
200 - 220				25.0	54.0	43.0	98.0	110.0				

Calcic Horizon

mg/L in Pipe Two. The generally low chloride concentrations within the pipes are an indication that the pipes act as conduits for downward water movement. The much higher chloride concentrations in the calcic horizons indicate that much less water is available to carry chloride downward. Therefore, the different chloride concentrations within and outside the pipe support our hypothesis that on surfaces with indurated calcic horizons in arid New Mexico, locations with negligible downward water fluxes are intermixed with sites that have considerable downward fluxes.

3.3.4 Hydraulic Properties

The saturated hydraulic conductivities measured in the indurated stage IV calcic horizon and the eolian and fluvial sediments are, respectively, 1, 186-195, and 52-60 cm/day. Thus, the saturated hydraulic conductivity of the calcic horizon is about two orders of magnitude less than that of the filling materials. The saturated hydraulic conductivity of the eolian pipe filling is about four times higher than that of the fluvial pipe fillings.

Figure 3-4 presents the measured water retention curves of the soils overlaying the calcic horizons and filling the pipes. These curves are typical for their textures. Measuring the water retention properties of the indurated stage IV calcic horizon, several attempts to insert TDR probes resulted in the sample breaking apart. Therefore, a representative water retention curve measured by Stakman and Bishay (1976) in an indurated calcic horizon in a loamy sand has been used for this study (Figure 3-5). The measured saturated hydraulic conductivities and the water retention curves (Figure 3-4)

Figure 3-4. Water retention curves measured in the pipe fillings and soils overlying the calcic horizons.

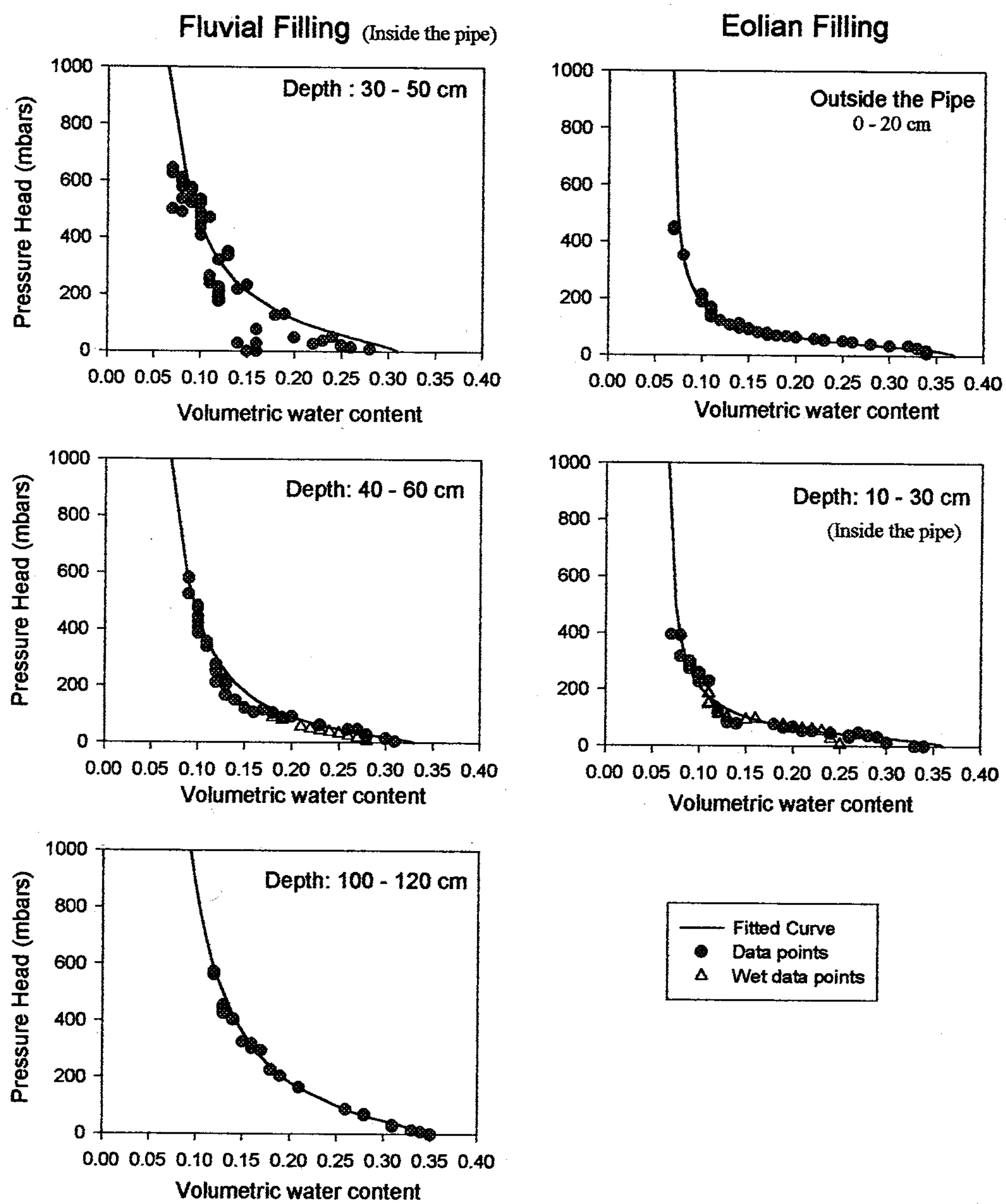
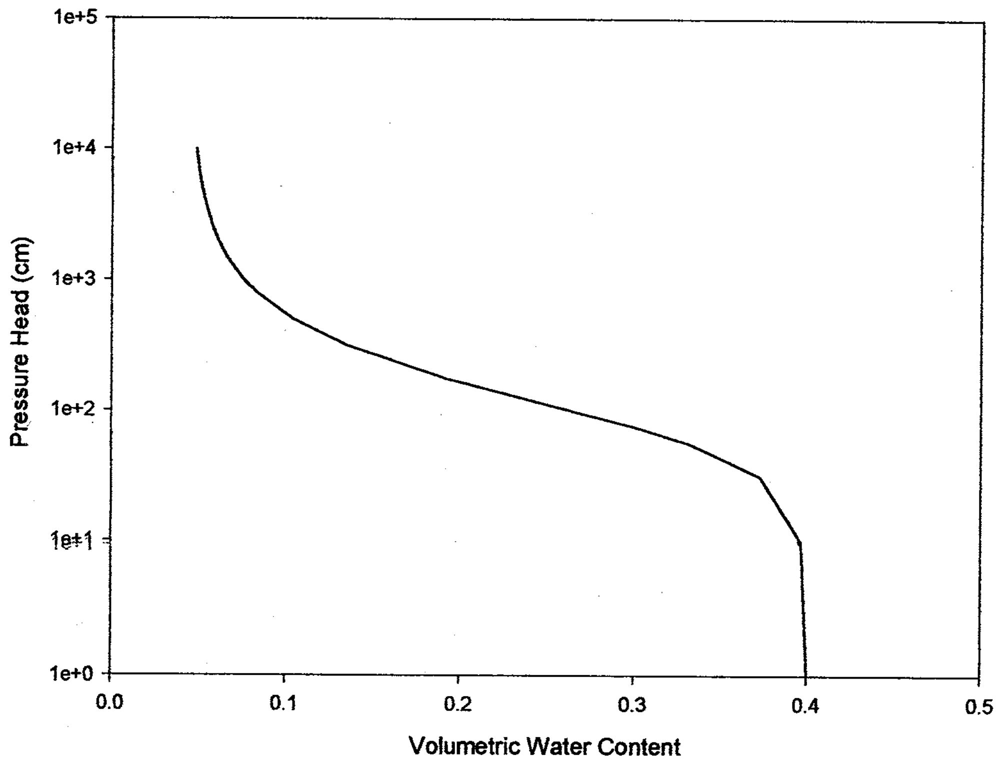


Figure 3-5. Water retention curve measured by Stakman and Bishay (1976) in an indurated calcic horizon in loamy sand in Egypt.



were used to derive van Genuchten parameters which are presented in Table 3-5.

3.3.5 A Conceptual Model for Water Movement Through Indurated Calcic Horizons

In this section I will formulate a conceptual model for downward water flow through indurated calcic horizons using the measurements of carbonate and chloride contents within and outside the pipes. To facilitate this process I have prepared visual interpolations of the carbonate and chloride measurements in the eight profiles of Pipe One (Tables 3-2 and 3-4). Figures 3-6 and 3-7 are spatial interpolations of all carbonate and chloride measurements inside and outside Pipe One. Figure 3-8 shows plots of the carbonate and chloride content with depth of two representative profiles inside (P4) and outside (P1) Pipe One. In addition, I prepared Figure 3-9 showing the sand and clay content with depths inside (P4) and outside (P1) Pipe One. Figures 3-6 and 3-7 clearly demonstrate that the amounts of carbonate and chloride inside the pipe (profiles P3, P4, P5, and P6) are considerably lower than outside the pipe in the calcic horizon (profiles P1, P2, P7, and P8). The same feature is clearly demonstrated in Figure 3-8. Figure 3-9 even suggests that the clay particles tend to wash out of the pipe. Therefore, these figures are strong evidence in support of our hypothesis that downward water fluxes inside pipes are much higher than outside the pipe.

The match between carbonate and chloride distributions outside Pipe One (fluvial filling) indicates a strong increase of chloride concentration at the interface

Table 3-5. Van Genuchten parameters derived from my measurements in the laboratory with the exception of θ_s, θ_r, α, and n for the calcic horizon. The latter parameters have been derived by fitting the van Genuchten model to the water retention curve presented in Figure 3-5.

Soil	Depth (cm)	K_{sat} (cm/day)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	α (1/cm)	n (-)
Eolian	0 - 20	195	0.37	0.060	0.019	2.00
	10 - 30	186	0.37	0.009	0.037	1.65
Fluvial	10 - 30	56	0.31	0.001	0.015	1.60
	40 - 60	60	0.34	0.020	0.028	1.50
	100 - 120	52	0.37	0.005	0.015	1.40
Calcic Horizon	80-100	1	0.40	0.045	0.013	1.95

Figure 3-6. Spatial interpolation of carbonate contents (%) measured in the eight profiles (P1-P8) inside and outside Pipe One based on data presented in Table 3-2.

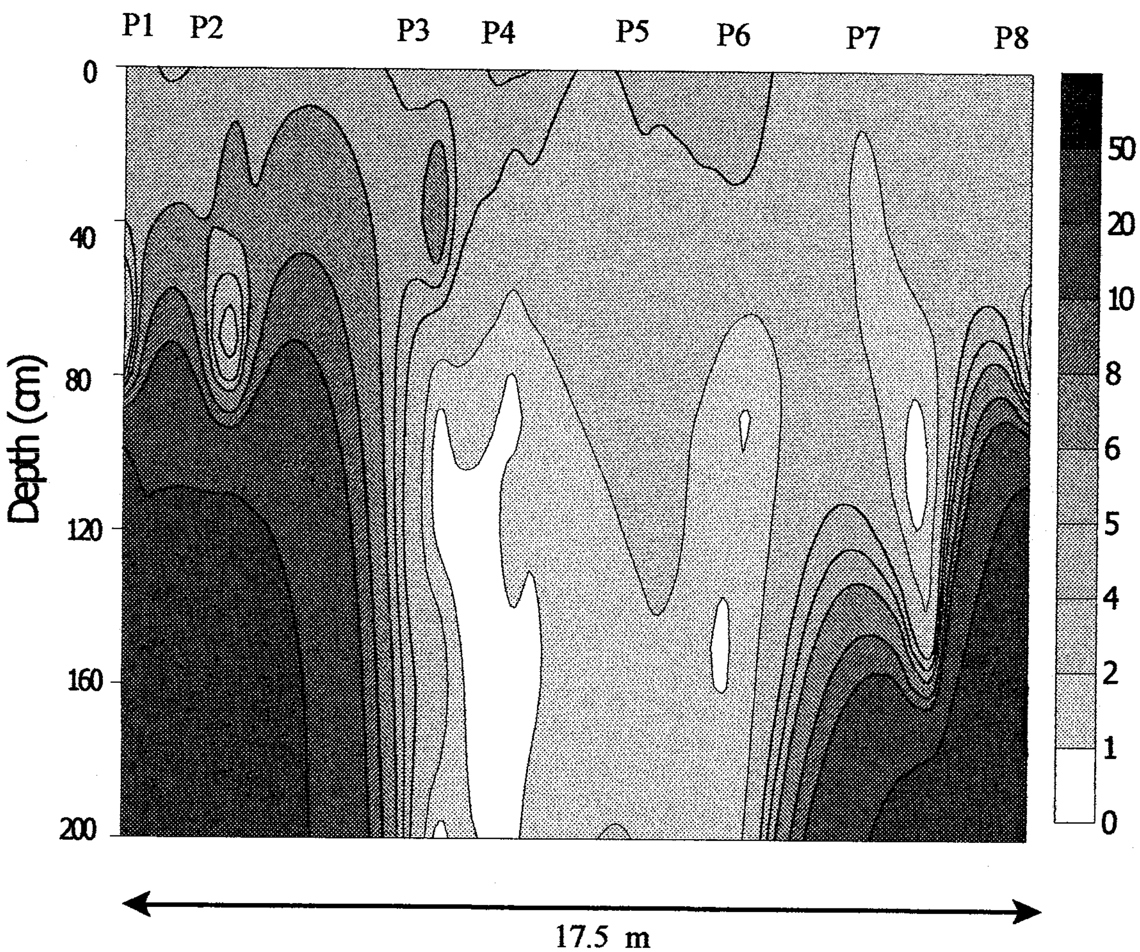


Figure 3-7. Spatial interpolation of chloride concentrations (mg/l) measured in the eight profiles (P1-P8) inside and outside Pipe One based on the data presented in Table 3-4.

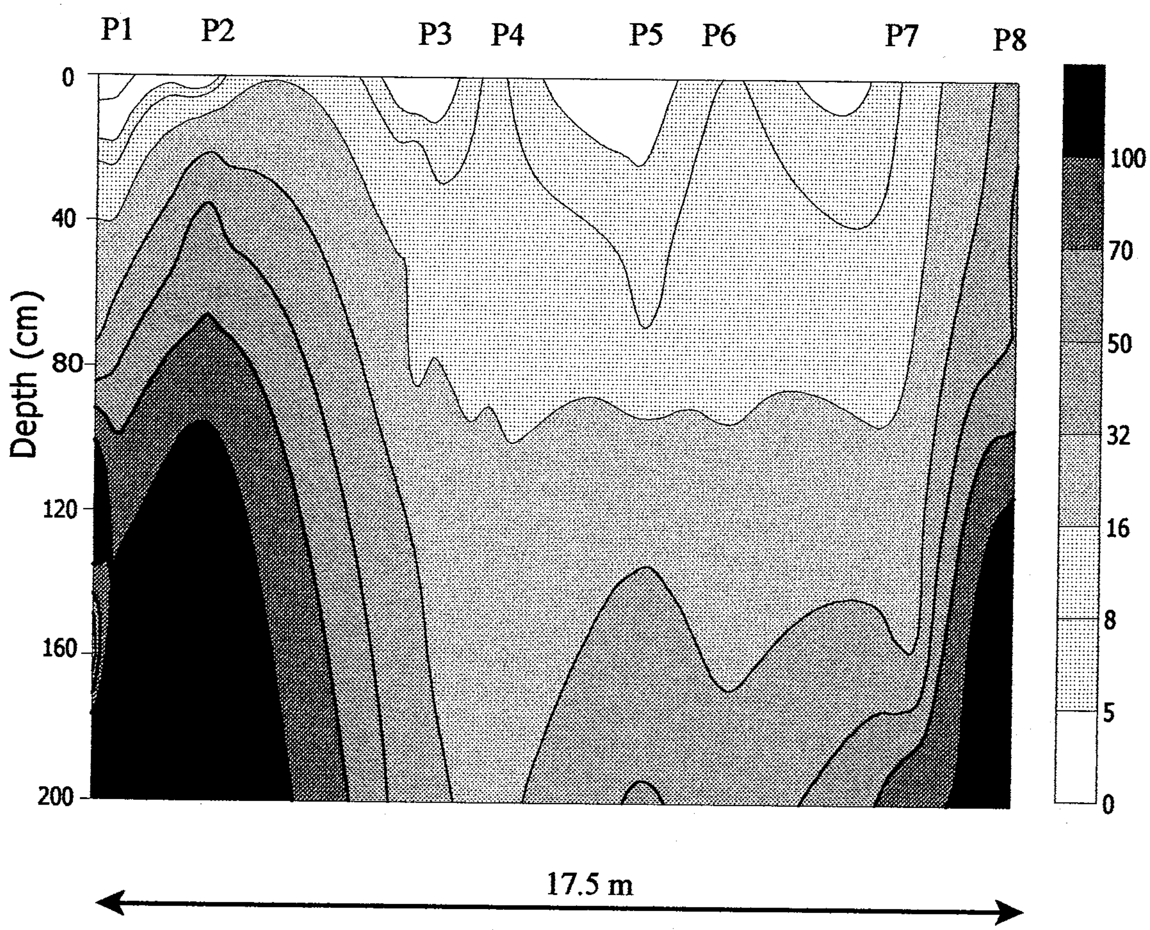


Figure 3-8 Depth profiles of carbonate content (%) and chloride concentrations (mg/l) inside and outside Pipe One based on data from tables 3-2 and 3-4 (P1 and P4).

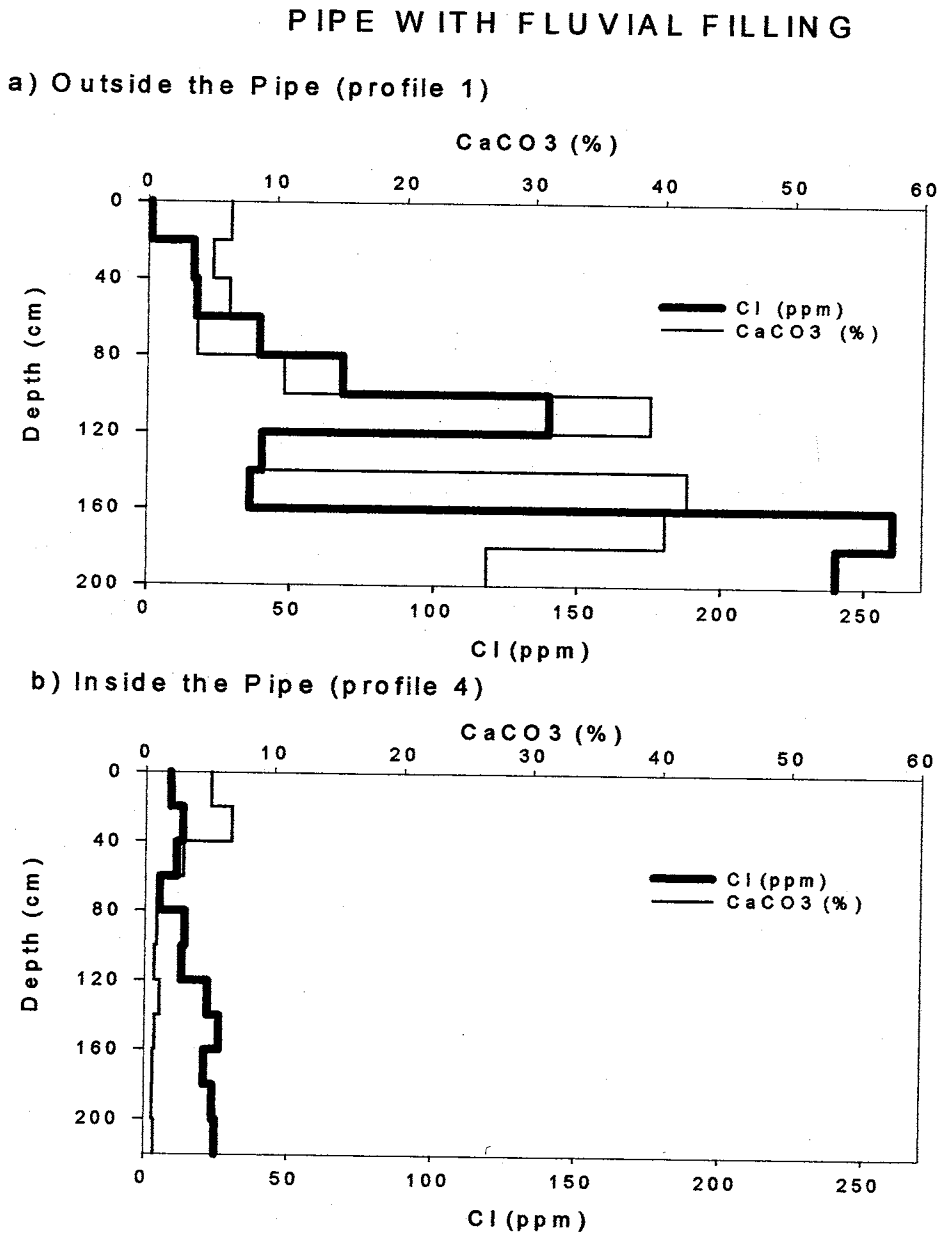
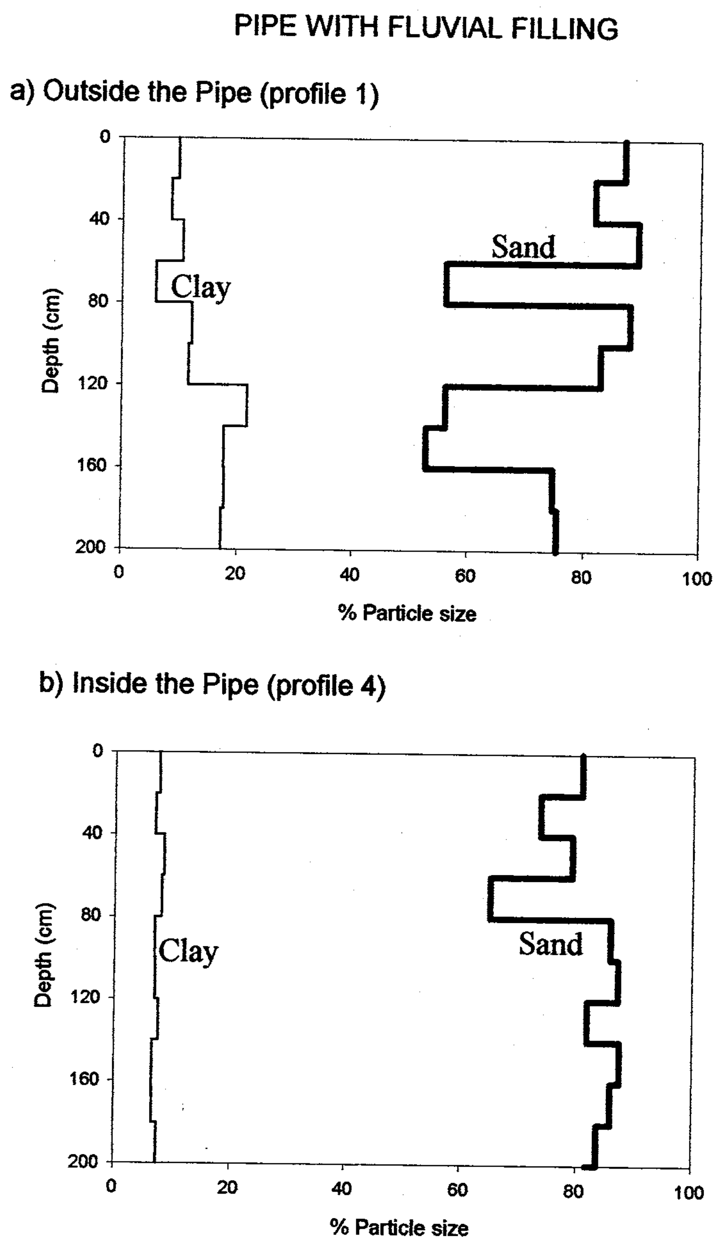


Figure 3-9 Depth profiles of sand and clay content (%) and chloride concentrations (mg/l) inside and outside Pipe One based on texture measurements in Profiles 1 and 4 (see Tables 3-1).



between overlying soil and indurated calcic horizon. Water flow through the calcic horizon is so restricted that only limited leaching of chloride occurs. Inspection of the chloride contents presented in Table 3-4 corroborate this finding. For example, in P1 of Pipe One the chloride content increases from 68 ppm at depth 80-100 cm in the fluvial filling to 140 ppm at depth 100-120 cm in the calcic horizon. No such sudden increase is found at the interface between overlaying soil and calcic horizon outside Pipe Two (eolian filling). For example, in P1 of Pipe Two the chloride content even decreases from 0.5 ppm at depth 40-60 cm in the soil to 0.2 ppm at depth 60-80 cm in the calcic horizon to 12 ppm at depth 80-100 cm in the calcic horizon. This suggests leaching in the top layer of the calcic horizon, possibly by a lateral flux through the calcic horizon towards the pipe in the eolian soil. Therefore, I hypothesize that the hydraulic characteristics of the pipe fillings determine not only the amount of downward water movement but also the long term water movement patterns.

The data presented in this chapter qualitatively support my hypothesis that on surfaces with indurated calcic horizons in arid New Mexico locations with negligible recharge are intermixed with sites that produce considerable recharge. There is also evidence that the hydraulic properties of the pipe fillings affect downward fluxes and water movement patterns. In the next chapter I will use a two-dimensional unsaturated water flow model to analyze quantitatively the data presented in this chapter.

4 - SIMULATION OF WATER FLOW THROUGH INDURATED CALCIC HORIZONS

The data presented in Chapter 2 leave no doubt that pipes in indurated calcic horizons are a common feature on the La Mesa surface in New Mexico. The physical measurements presented in Chapter 3 reveal that the chloride concentrations in the pipe fillings are considerably lower than those found in the surrounding calcic horizons. This suggests that water fluxes through pipes are larger than those through the surrounding calcic horizons. However, it is not possible to directly determine soil water dynamics from the chloride distributions within and outside the pipes. For example, it is not known whether the low chloride contents result from one large extreme precipitation event or from continuous leaching as a result of deep percolation during average precipitation years. Another issue is whether the pipes indeed will enhance overall deep percolation rates over the La Mesa surface or merely cause an uneven horizontal distribution of those rates. Finding an answer to these questions by actual field measurements of deep percolation rates under the arid conditions of New Mexico could take many years (Hendrickx and Walker, 1997). Therefore, computer models are used to assess water flow through the pipes.

Since a complete model study for assessment of all factors that affect ground water recharge through pipes falls outside the scope of the current study, the objective of this chapter is to explore whether a representative pipe in a bare soil would affect downward water fluxes under the climatic conditions of arid New Mexico.

4.1 METHODS AND MATERIALS

The approach to assess the effect of pipes on water flow is straightforward. I simulated downward water fluxes in soil profiles with and without pipes and compared the fluxes. Since the pipes have been found in two different soil materials (eolian and fluvial) a total of four simulations were conducted (Table 4-1). In this phase of the study I am only interested in establishing whether pipes affect downward fluxes in a bare soil. I will not consider the effects of vegetation or different pipe shapes and distances. I conducted simulations for a small representative pipe found with both the fluvial and eolian soils (Figures 1-1, 2-2, and 2-6).

Soil water flow through the indurated calcic horizons with pipes was modeled with the HYDRUS-2D simulation package (Šimunek et al., 1999) of the U.S. Salinity Laboratory at Riverside, California. HYDRUS-2D is a Microsoft Windows based modeling environment for simulating two-dimensional water, heat, and solute movement and root water uptake in variably saturated soil. The flow equations are solved numerically using a Galerkin-type linear finite element scheme. The software includes a mesh generator and graphical user interface.

For the simulation of water flow through pipes in indurated calcic horizons, I used a quasi three-dimensional region exhibiting radial symmetry about the vertical

Table 4-1. The four different soil configurations evaluated in the simulations.

Simulation	Soil	Pipe Present	Pipe Diameter Top (m)	Pipe Diameter Bottom (m)	Depth Calcic Horizon (m)
E-P	Eolian	no	-	-	0.65 m
E+P	Eolian	yes	4.0 m	0.74 m	0.65 m
F-P	Fluvial	no	-	-	0.65 m
F+P	Fluvial	yes	4.0 m	0.74 m	0.65 m

axis. The Richards equation was solved to simulate unsaturated water flow in a soil cylinder with a radius of 2 m and depth of 3 m. The configuration of the soil materials for simulation of pipe flow is presented in Figure 4-1. For the simulation of water flow outside the pipes the configuration was changed to a 0.65 m layer of soil overlaying a 2.35 m thick calcic horizon. A finite element mesh was generated by the mesh generator provided with the HYDRUS-2D program. Different mesh sizes and densities were examined to obtain a water mass balance error of less than 0.5 % during simulations. The optimal mesh for simulation of water flow through pipes was constructed in such a way that small triangular elements were placed in those areas where the highest water fluxes occur: near the soil surface, at the interface between pipe filling and topsoil, and at the interface between the filling and the calcic horizon (Figure 4-2). This mesh has a total of 3766 mesh points, 11046 mesh edges, and 7281 mesh triangles. Observation nodes were placed on 17 different locations in the flow domain for analysis of flow patterns inside and outside the pipe (Figure 4-3).

The top boundary condition of the soil cylinder was determined by the atmospheric conditions. I used daily precipitation data and potential evapotranspiration data from Las Cruces during the period 1960-1990 for our simulations. The daily precipitation data were recorded at the Jornada research facility on the New Mexico State University College ranch, 50 km northeast of Las Cruces in Dona Aña County, New Mexico (Malm, 1994). The daily potential evapotranspiration rates for the period 1983-1994 were calculated from meteorological measurements at the Leyendecker Weather Station of New Mexico State University. This station is about 68 km south of

Figure 4-1. Quasi three-dimensional simulation domain for simulation of water flow through pipes.

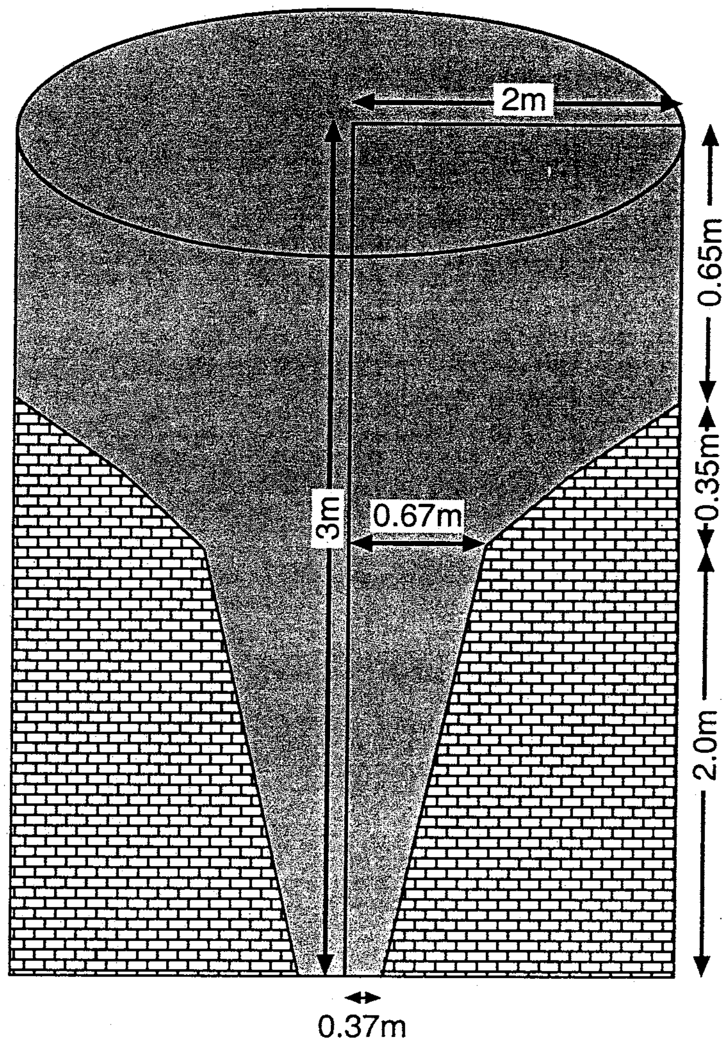


Figure 4-2. Finite element mesh used for the simulation of water flow through a pipe.

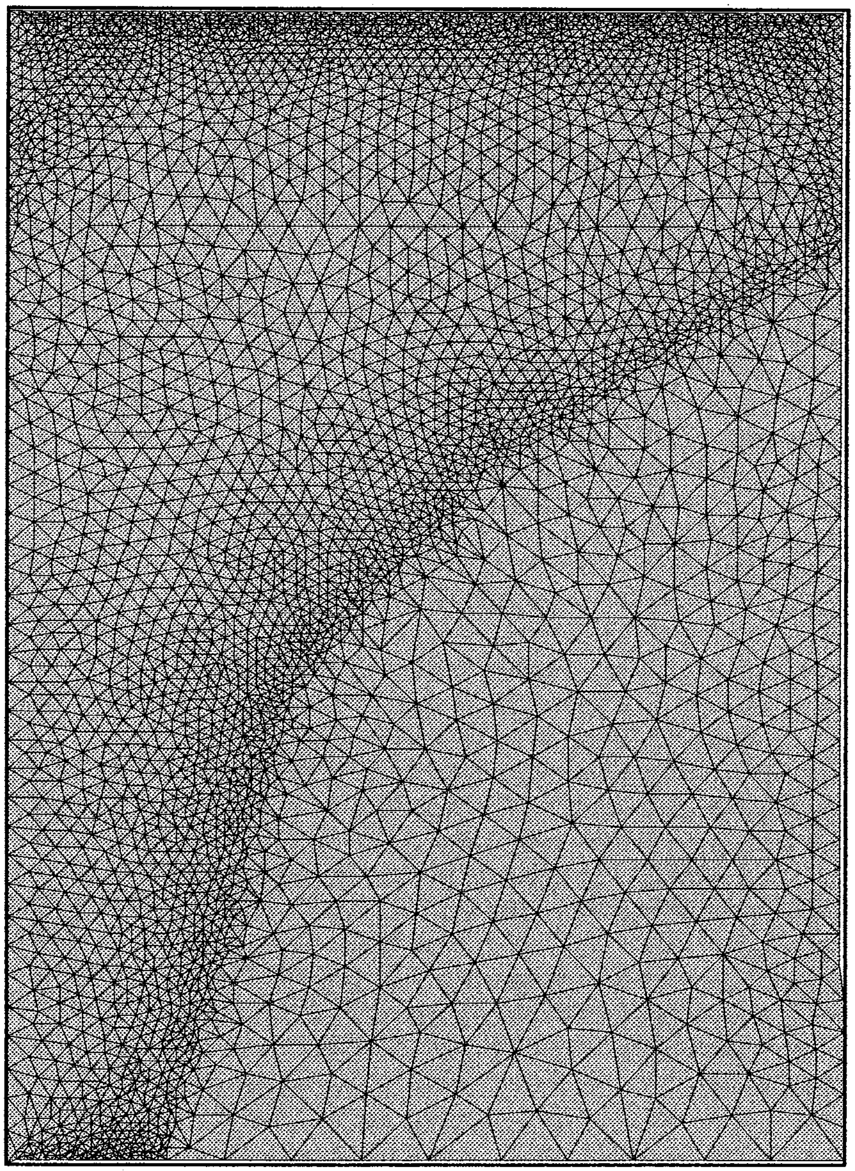
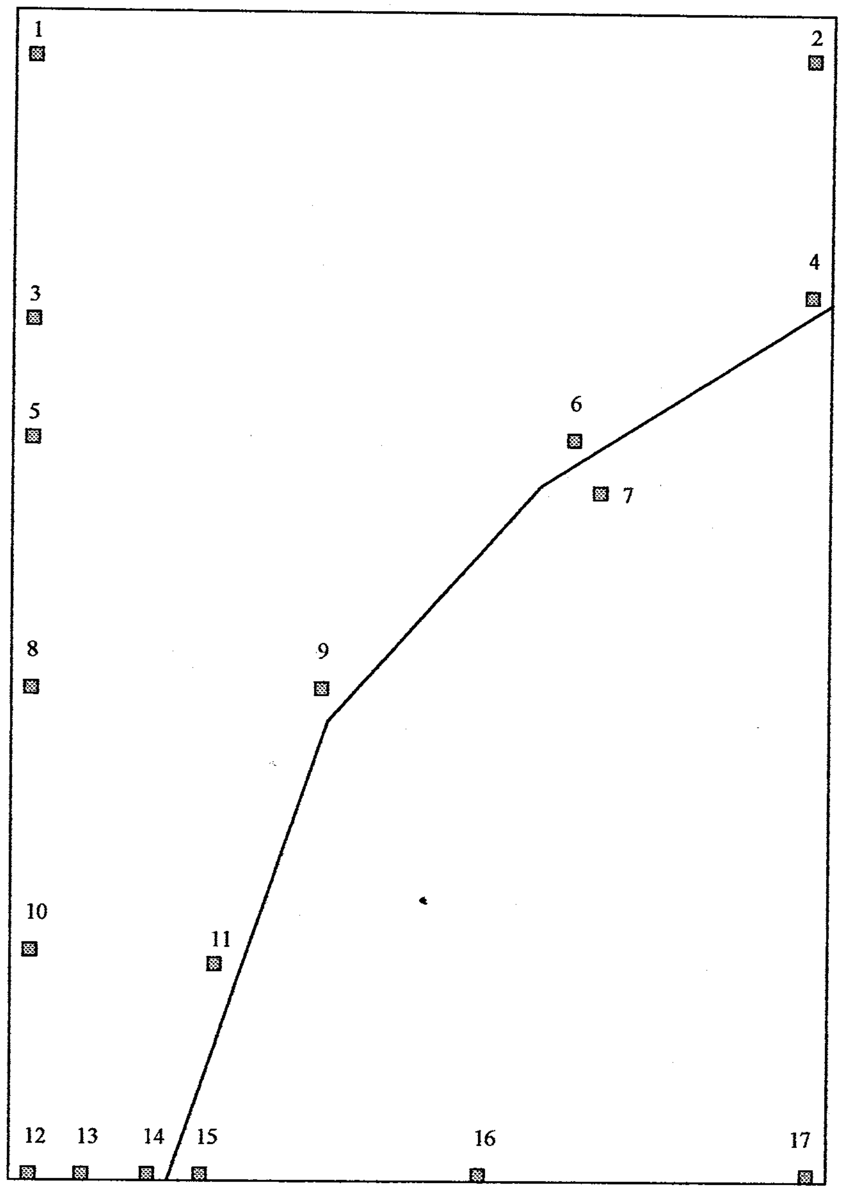


Figure 4-3. Observation nodes for analysis of the flow patterns inside and outside the pipe.



the Jornada weather station. The daily potential evapotranspiration rates from 1983-1994 were averaged on a day-of-year basis and the daily averages were used as the daily input in the model. A free drainage condition representing unit gradient was assigned to the bottom boundary of the simulation domain. A no-flux boundary condition was imposed on two sides of the flow domain.

The initial condition was set at a uniform soil water pressure of -10 m throughout the profile. I conducted simulations for periods of 60 to 90 years using two or three repetitions of the 1960-1990 weather data. Results from the first 30 or 60 years' simulation were not included in the final analysis because of the assumption that during this period the model adjusted its initial condition to prescribed boundary conditions. The model was considered in equilibrium with its boundary conditions when a clear correlation was observed between precipitation events and recharge rates (see also Table 4-3). The hydraulic properties of the eolian and fluvial sands as well as the calcic horizon were obtained from Table 3-5 by selecting representative values. The van Genuchten parameters used in the computer simulations are presented in Table 4-2.

4.2 RESULTS AND DISCUSSION

4.2.1 Meteorological Conditions

Figure 4-4 presents the daily precipitation values for the period 1960-1990. The mean precipitation is 0.23 m per year. Comparing the mean annual precipitation with the annual totals shows that the years 1960-1967 were generally drier than average

Table 4-2. The Van Genuchten parameters used in the simulations.

Soil	K_{sat} (cm/day)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	α (1/cm)	n (-)
Eolian	200	0.37	0.015	0.035	1.80
Fluvial	50	0.34	0.005	0.015	1.60
Calcic Horizon	1	0.40	0.045	0.013	1.95

Figure 4-4. Daily precipitation at Las Cruces during the period 1960-1990.

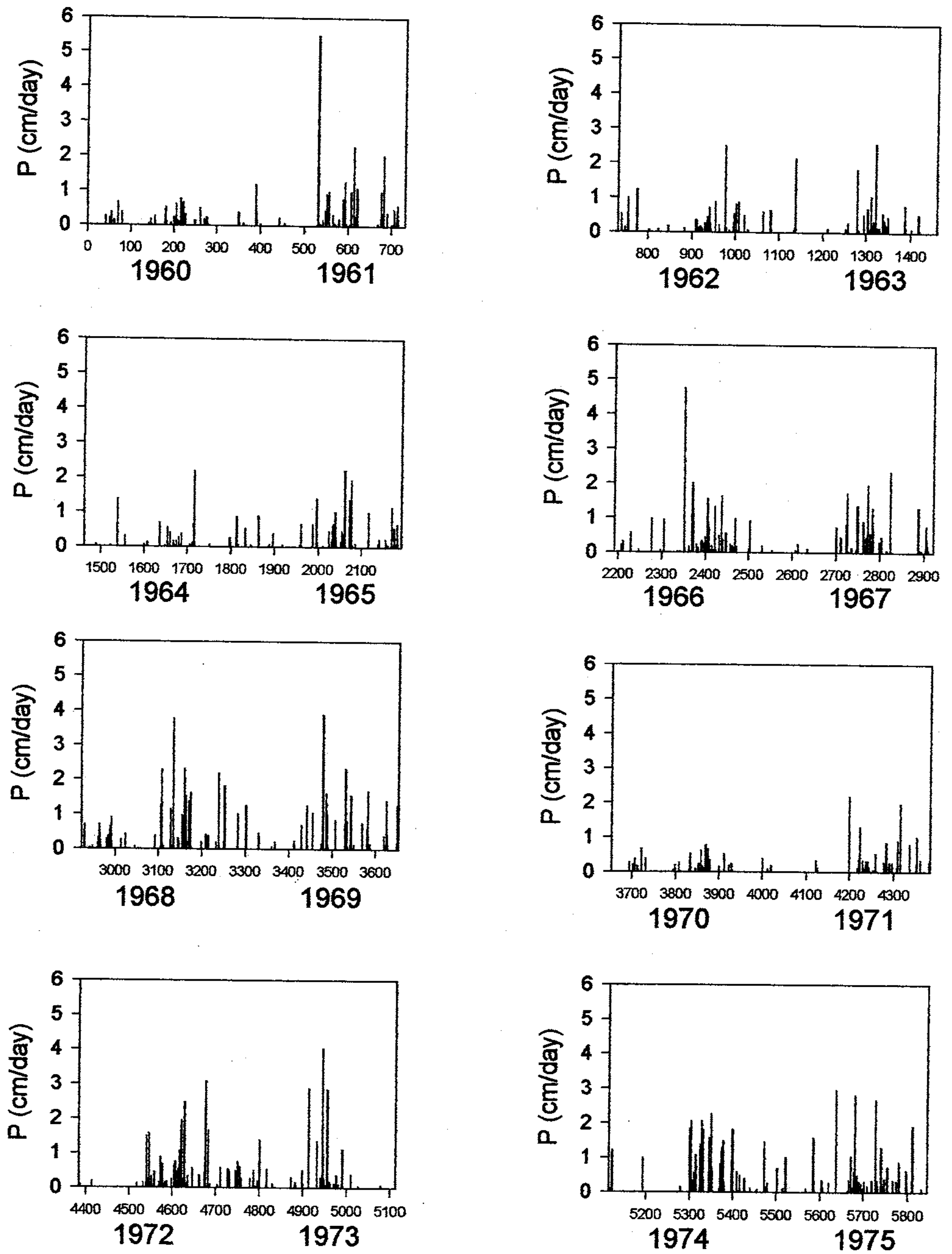
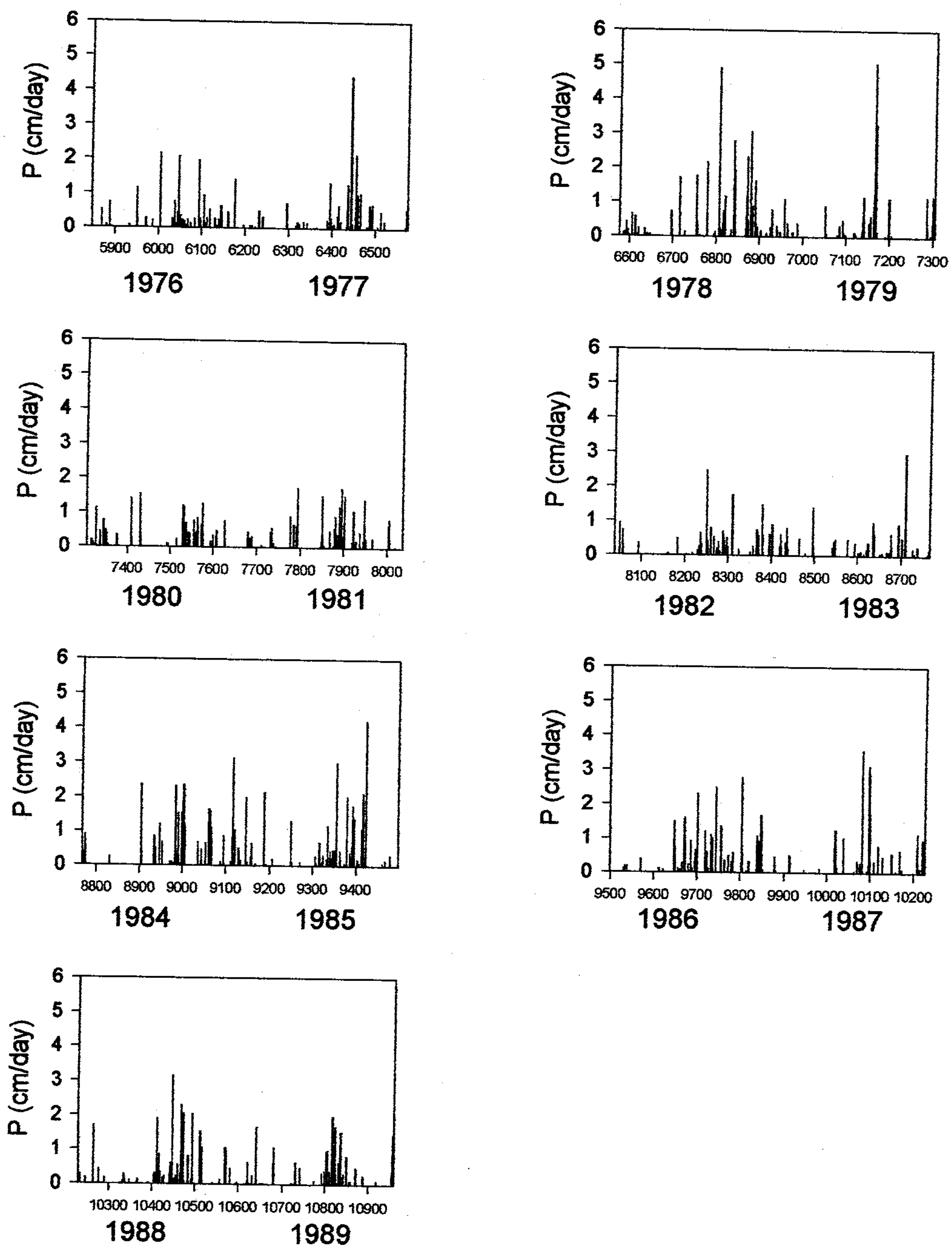


Figure 4-4. Continued. Daily precipitation at Las Cruces during the period 1960-1990.



while the 1970s and 1980s were wetter (Figure 4-5). The rainfall variability is quite large, both within and between years.

Daily potential evapotranspiration (PET) rates were available only for the period 1983-1995. For the generation of daily PET rates for the entire period 1960-1990 I followed Kearns and Hendrickx (1998) and used the mean daily average PETs calculated for the period 1983-1995. Thus, I use the same mean daily PET value for a given day for thirty years of the simulation (Figure 4-6). This procedure will cause overestimation of the true PET on days with precipitation events since averaging can't reflect the cooler temperatures and cloudy conditions which occur during precipitation and thunderstorm events. Consequently, the PET averaging procedure to generate daily PET values for the period 1960-1990 will result in an underestimation of downward water fluxes. However, use of the averaged data is considered justified since the actual and daily mean PETs are strongly correlated (Kearns and Hendrickx, 1998).

4.2.2 Downward Water Fluxes

In soil profiles with and without pipes I can define four different downward water fluxes at 3 m depth. The first flux occurs in a soil profile with an indurated calcic horizon without pipes ($q_{without\ pipe}$) while the three other downward fluxes occur in a soil profile with an indurated calcic horizon with pipes (see Figure 2-4). Those three fluxes are: an areally averaged downward water flux for the entire soil ($q_{with\ pipe}$), a downward water flux through the bottom of the pipe only ($q_{inside\ pipe}$), and a downward water flux through the indurated calcic horizon outside the pipe ($q_{outside\ pipe}$). Since the latter flux was always

Figure 4-5. Annual precipitation totals and mean annual precipitation during the period 1960-1990.

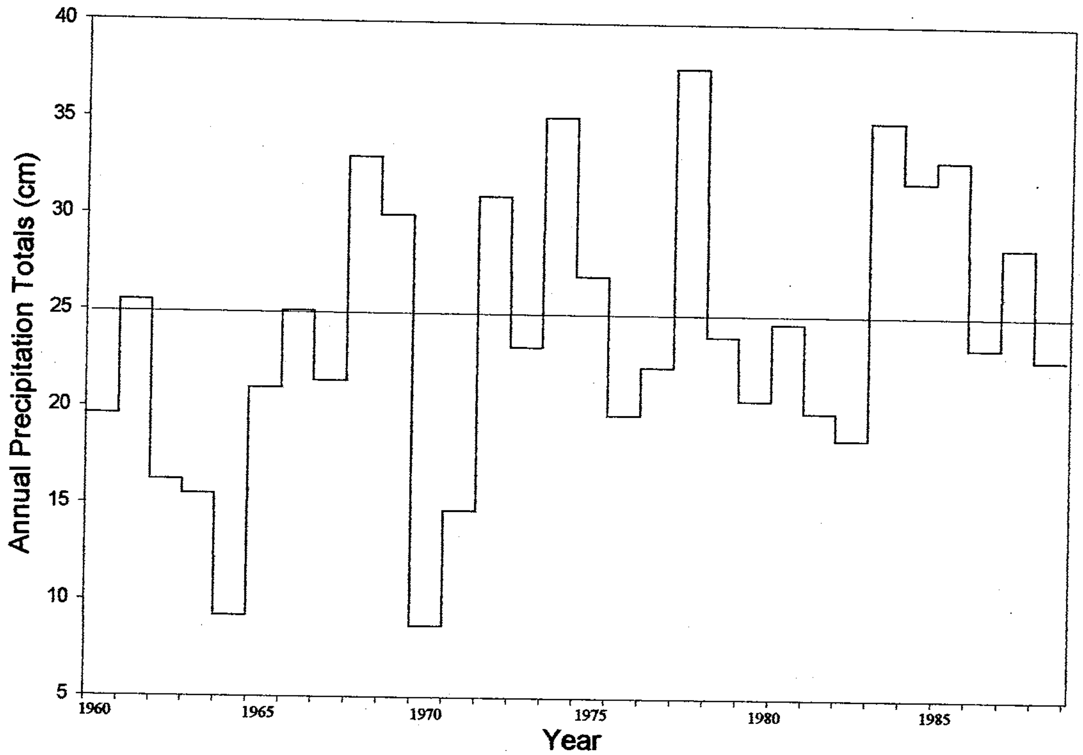
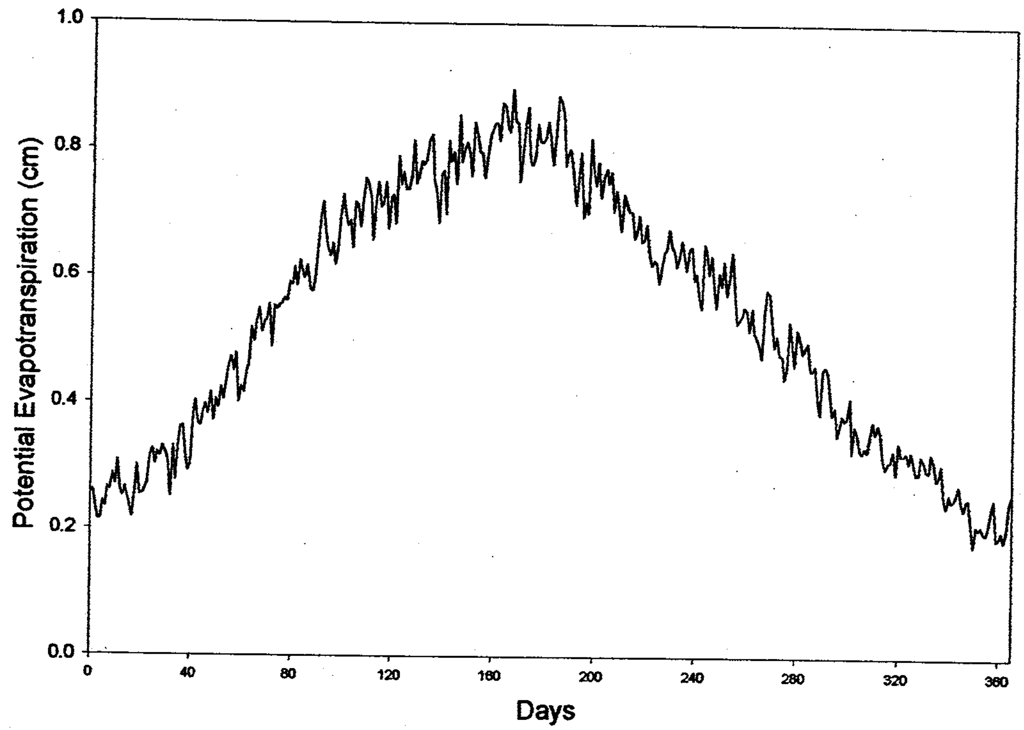


Figure 4-6. Mean daily potential evapotranspiration rate for each day of the year based on meteorological measurements during the period 1983-1995.



equal or somewhat smaller than $q_{without\,pipe}$ in our simulations I do not consider it in this study. Figure 4-7 presents the simulated values for $q_{without\,pipe}$ and $q_{with\,pipe}$ for the fluvial and eolian soils during the period 1960-1990. The downward fluxes in profiles without pipes ($q_{without\,pipe}$) vary from less than 0.03 mm per year in the fluvial soil to approximately 3 mm per year in the eolian soil. These values fall well into the range of field determined recharge fluxes from 0.01 to 37 mm per year that has been reported for southern New Mexico and West Texas by Scanlon (1992), Stephens and Knowlton (1986), and Stephens (1995). The difference between the downward fluxes through the fluvial and the eolian soils is more than two orders of magnitude which leads to an important observation. Downward water fluxes in arid soils with indurated calcic horizons are not solely determined by the hydraulic properties of the indurated horizon but by the hydraulic properties of the overlying soil as well.

A large increase in downward water flux occurs if a pipe is present. The downward fluxes ($q_{with\,pipe}$) now vary from about 0.1-0.8 mm per year in the fluvial fill to about 4-9 mm per year in the eolian fill. The effect of the pipe is strongest in the fluvial soil where the downward flux increases by more than one order of magnitude while in the eolian soil the flux approximately doubles. The increase in $q_{with\,pipe}$ is caused by a large increase in $q_{inside\,pipe}$ which amounts to 3-20 and 24-95 mm per year in the fluvial and eolian filling, respectively, (Figure 4-8). The $q_{inside\,pipe}$ simulated in the pipe with eolian filling is quite similar with the flux measured in a bare lysimeter (depth 6 m, diameter 2 m) filled with a loamy fine sand in the Chihuahuan Desert near Las Cruces. Wierenga and Jones (1995, pers. communication) measured during 1989-1994 an

Figure 4-7. Simulated downward water fluxes in fluvial and eolian soils with and without pipe during the period 1960-1990.

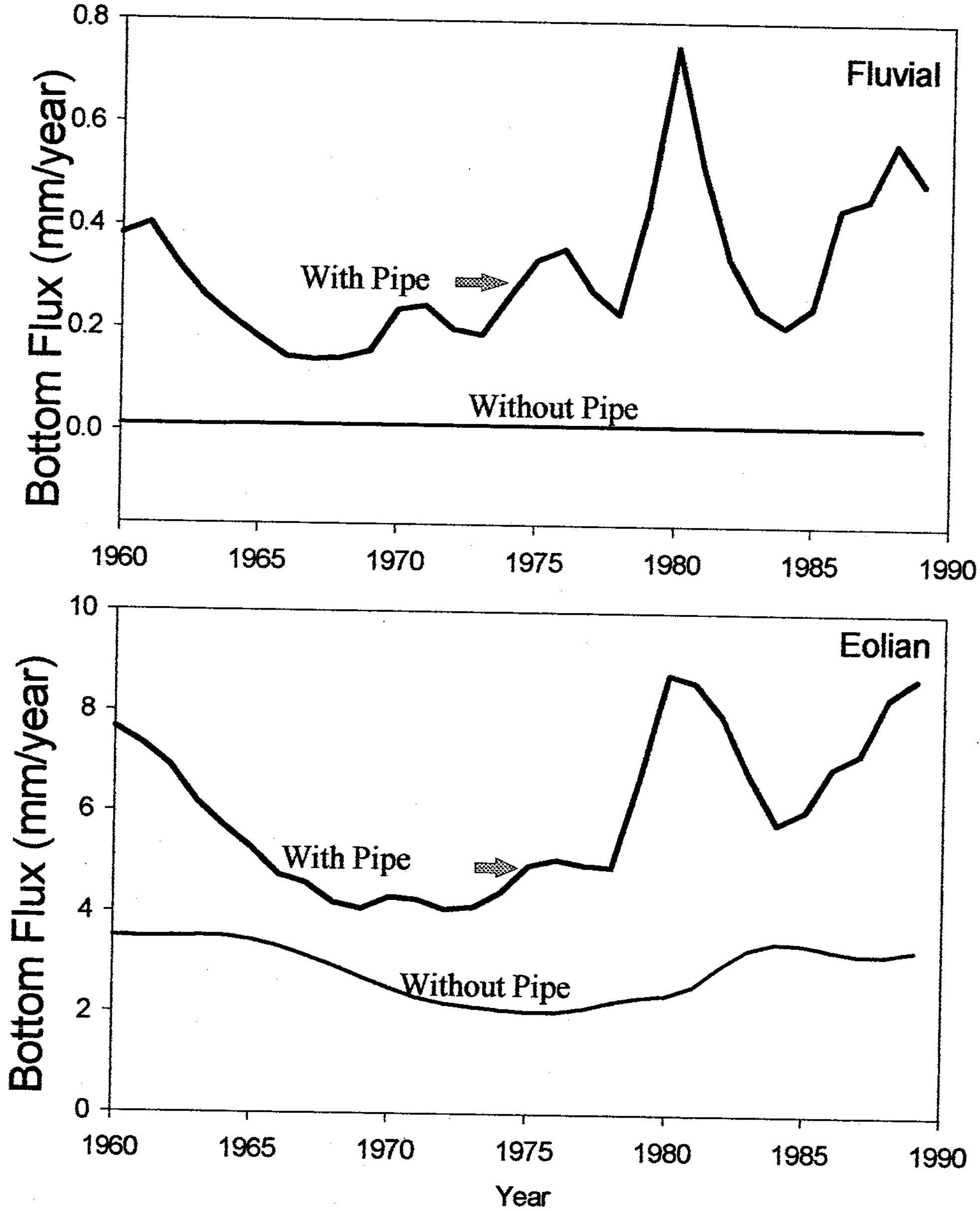
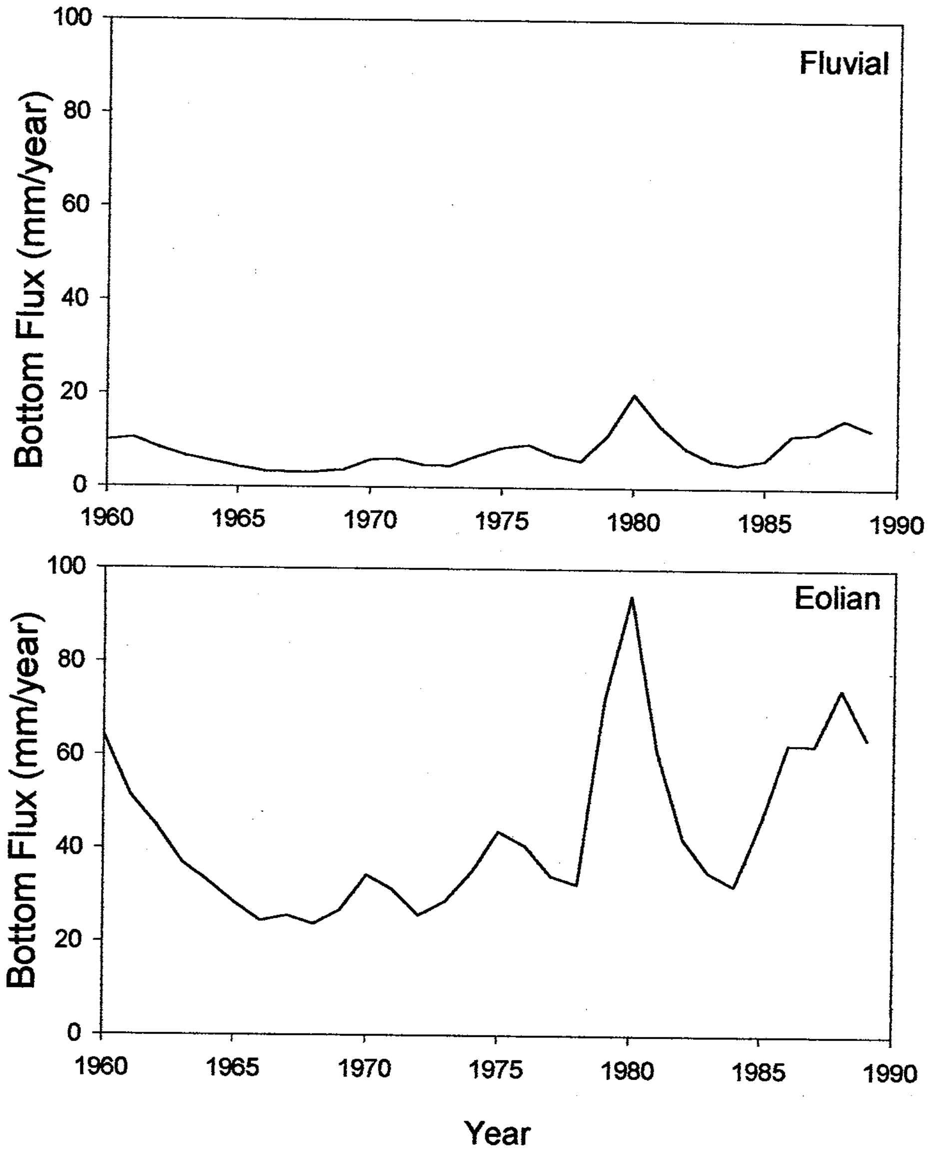


Figure 4-8. Simulated downward water fluxes through the bottom of a pipe in eolian and fluvial soils during the period 1960-1990.



average annual downward water flux in this lysimeter of about 50 mm per year, or 20% of the annual precipitation. These downward fluxes are of the same order of magnitude as the ones simulated through the eolian filled pipe. Therefore, the lysimeter measurements seem to validate our simulation results.

Our chloride measurements provide a validation of the relative magnitudes of the simulated fluxes. The mean chloride concentration measured inside Pipe One (fluvial filling) below depth 100 cm is 30 ppm while that in Pipe Two (eolian filling) is 9 ppm. This is an indication that the deep downward percolation flux in the eolian pipe is about three times larger than through the fluvial pipe. This is in reasonable agreement with the average annual simulated downward fluxes, $q_{inside\ pipe}$, of 8 mm/year in the fluvial pipe versus 44 mm/year in the eolian pipe (Figure 4-8). Thus, the chloride measurements also seem to validate our simulation results.

The simulated downward fluxes within ($q_{inside\ pipe}$) and outside pipes ($q_{without\ pipe}$ or $_{outside\ pipe}$) are 8.0 versus 0.02 mm/year and 43.8 versus 4.6 mm/year in the fluvial and eolian materials, respectively. In the fluvial soils $q_{inside\ pipe}$ is more than two orders of magnitude larger than $q_{outside\ pipe}$, while the difference in the eolian soil is about one order of magnitude. These results indeed do support our hypothesis that on surfaces with indurated calcic horizons in arid New Mexico, locations with negligible recharge are intermixed with sites that produce considerable recharge.

4.2.3 Soil Water Content Distributions Inside and Outside the Pipes

The temporal and spatial changes of the soil water content distribution inside and outside the pipes clearly demonstrate the dynamic flow processes. In this section I will discuss the changes of soil water content observed at the 17 observation nodes (Figure 4-3) during the period 1960-1990 in the fluvial and eolian filles pipes at different depths (Figures 4-9 and 4-10).

Figures 4-9A and 4-10A show the water content changes above the center of the pipe (node 1) and above its edge (node 2) at depth 5 cm where the base line soil water content is approximately 5% in the fluvial and eolian soils. However, there are many changes in soil water content over time, some as small as 2% others as large as 20%. A change of 2% in water content over a depth of 5 cm requires only 0.1 cm of precipitation which indicates that almost each precipitation event produces a rapid response near the soil surface. In the eolian soil, water content changes above the center of the pipe and above its edge are almost identical while the fluvial soil above the edge of the pipe becomes slightly wetter after a precipitation event and slightly drier during a dry period. Thus, at depth 5 cm soil water content changes basically mimic precipitation events.

At a depth of 60 cm many of the soil water content increases observed at the 5 cm depth are attenuated (Figures 4-9B and 4-10B). The water content changes become smoother over time and smaller as the high frequency peaks are filtered out by the soil. Whereas soil water content maxima at the 5-cm depth frequently reach values above 22% in the fluvial and eolian soils, most maxima at the 60-cm depth are between 10-13% with only one maximum exceeding 16% in both soils. Similar to the observations at the 5-cm depth, in the eolian soil the water content changes above the center of the pipe (node 3) and above its edge (node 4) are almost identical while the fluvial soil above the edge of

Figure 4-9 Soil water contents observed at the 17 observation nodes during 1960-1990 in the fluvial soil.

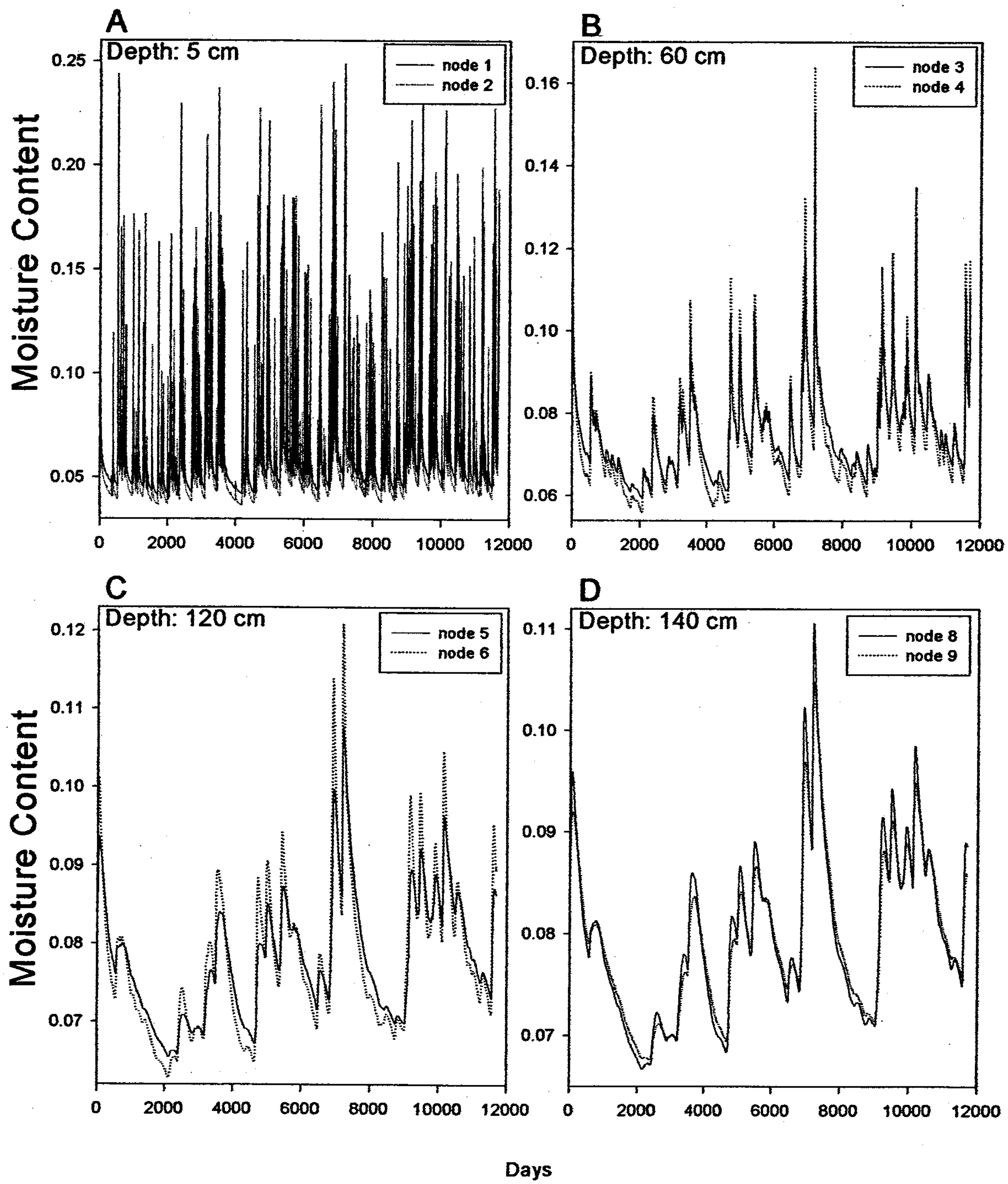


Figure 4-9 Continued. Soil water contents observed at the 17 observation nodes during 1960-1990 in the fluvial soil.

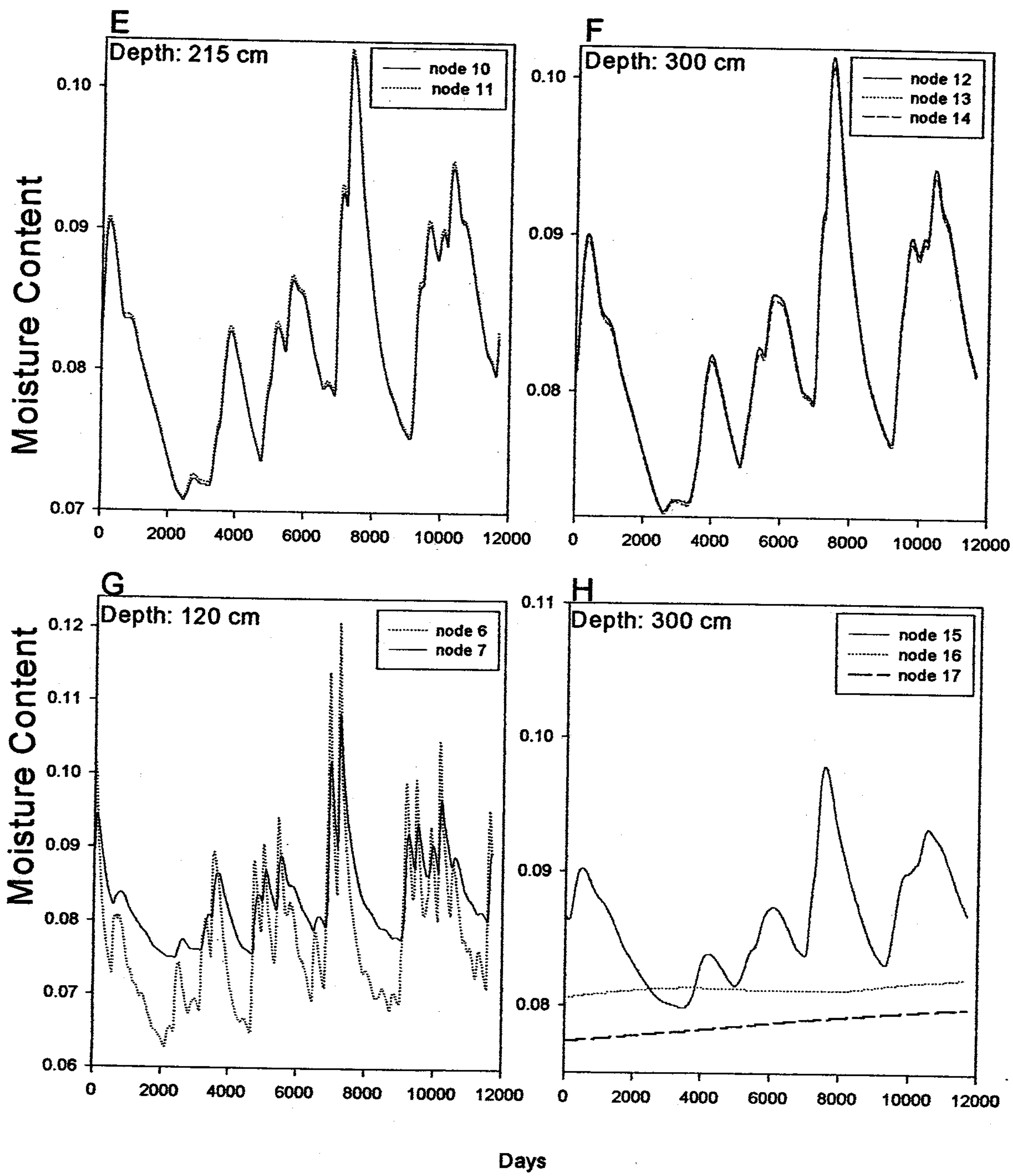


Figure 4-10 Soil water contents observed at the 17 observation nodes during 1960-1990 in the eolian soil.

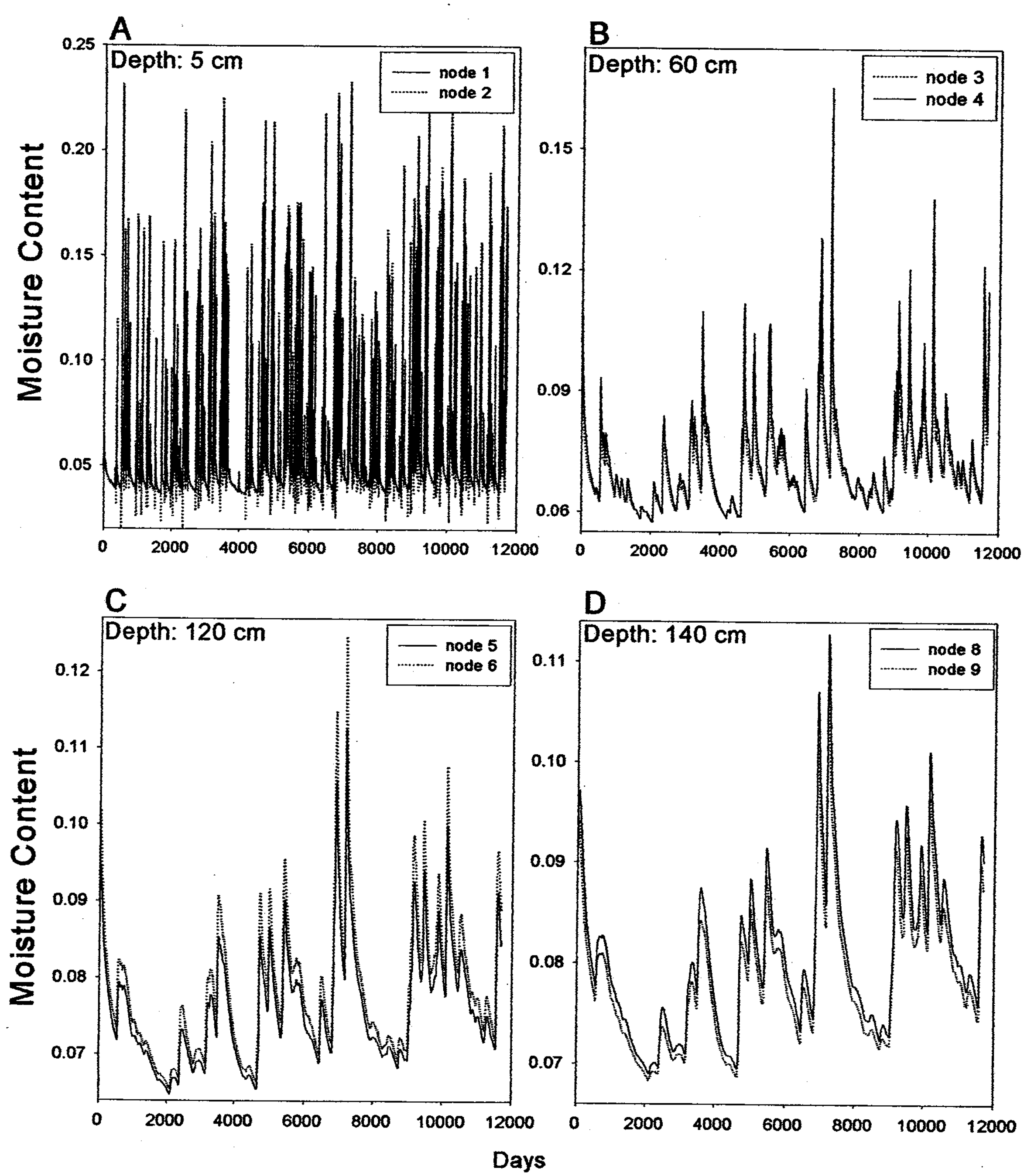
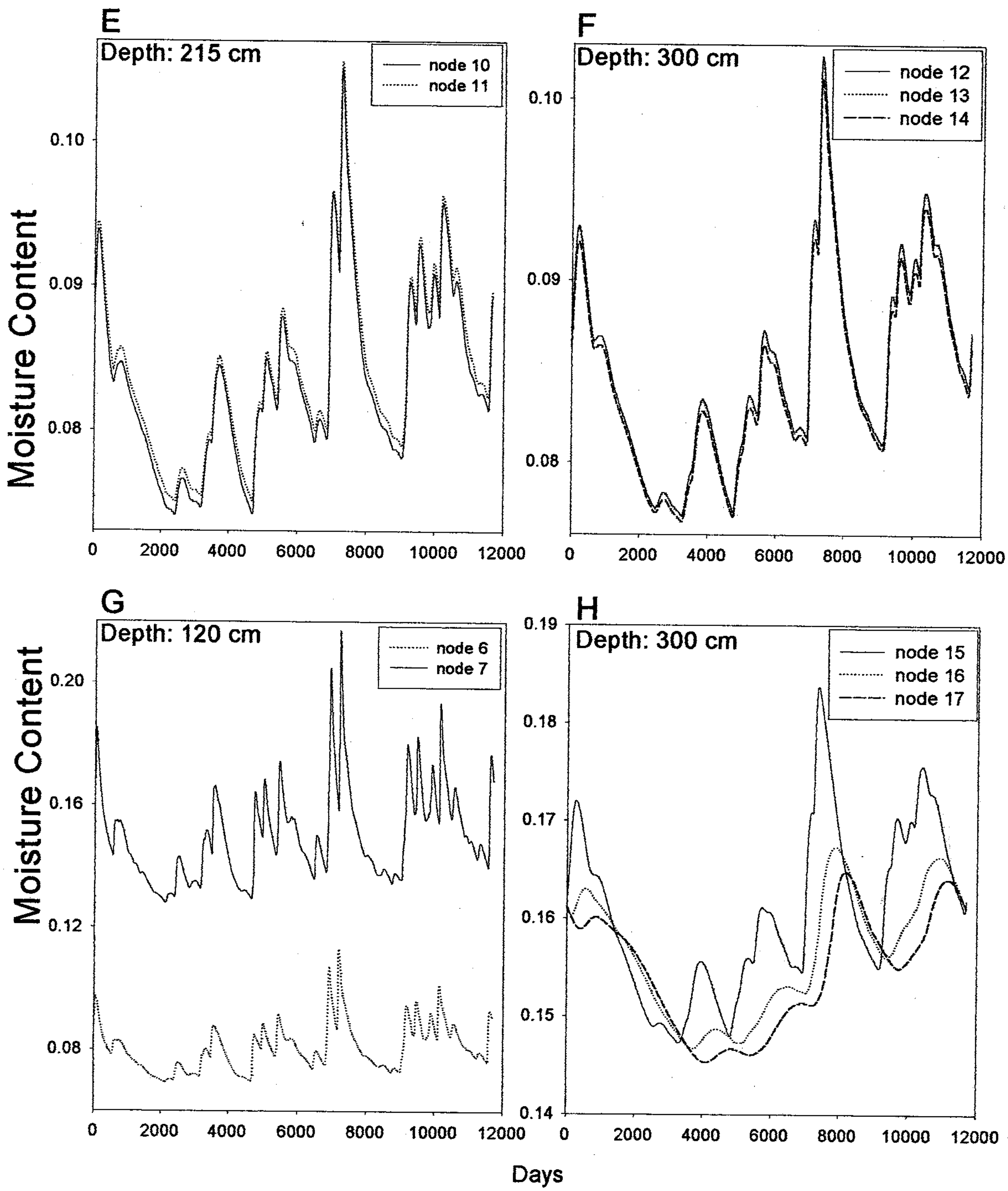


Figure 4-10 Continued. Soil water contents observed at the 17 observation nodes during 1960-1990 in the eolian soil.



the pipe (node 3) becomes slightly wetter after a precipitation event and slightly drier during a dry period. Whereas at the 5-cm depth soil water content changes basically mimic precipitation events, at the 60-cm depth only major precipitation events cause a response. In Figures 9A and 10A I have detected seventeen major increases in soil water content as a result of precipitation events that are approximately 10 mm or more. All these events cause a response at the 60-cm depth (Figures 9B and 10B) except one which has dampened out.

The pattern observed at depths 5 and 60 cm inside the pipe continues at depths 120 (Figures 4-9C and 4-10C) but changes at depths 140, 215, and 300 cm (Figures 4-9D through F and 4-10D through F). At the latter depths no or very small differences in water content are detected between the center of the pipe (nodes 8, 10, and 12) and the edge of the pipe (nodes 9, 11, and 14). Whereas at and above depth 120 cm the edge of the pipe (nodes 4 and 6) has higher water contents (0.5-2%) as a result of accumulation of water through lateral flow, no such accumulations have been detected at greater depths. Apparently, the dampening of the initial precipitation input by the soil at these depths allows sufficient time for a lateral water flow component to equalize the water content at depth.

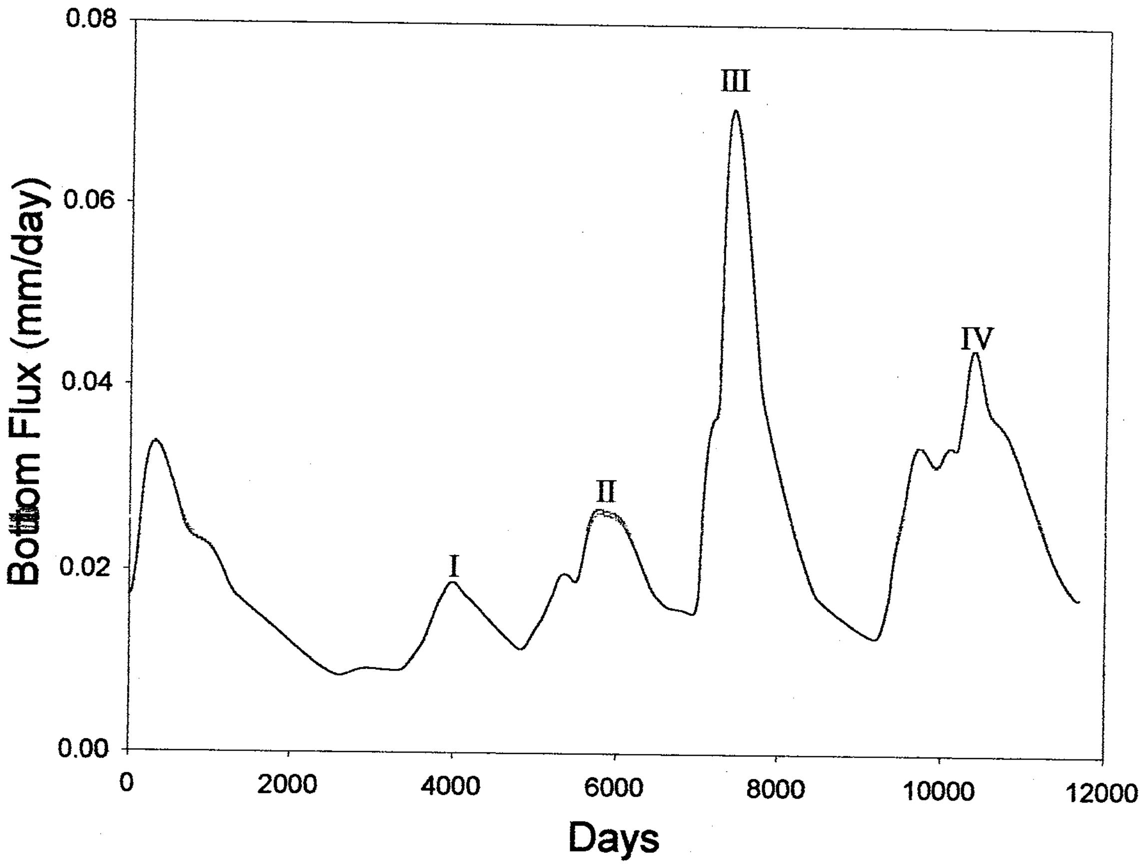
The number and size of the peaks of maximum soil water contents occurring at depths 5, 60, 120, 140, 215, and 300 cm (Figures 4-9A through F and 4-10A through F) demonstrate how the soil filters high frequency precipitation events at the soil surface to low frequency maximum downward water fluxes at depth. The seventeen peak precipitation events at depth 5 cm condense to only four major peak downward water fluxes at depth 300 cm in the fluvial and eolian soil. The only difference between the two soils is that the peaks in the eolian soils occur somewhat sooner than in the fluvial soils. As a result of this faster propagation more peaks can be distinguished in the eolian soil than in the fluvial soil. In the next section I will discuss with more detail the lag time observed at different depths in the two soils.

The pattern of the water content changes observed outside the pipe in the calcic horizon (nodes 7, 15, 16, and 17) appears similar to those inside the pipe but there are also important differences (Figures 4-9G through H and Figure 4-10G through H). Figures 4-9G and 4-10G present water content changes at depth 120 cm across the interface between soil (node 6) and calcic horizon (node 7). In both soils the pattern of peaks remains the same inside and outside the pipe indicating the dynamics of flow processes across the interface between soil and calcic horizon. In the eolian soil the water content is consistently higher inside the pipe (node 6) than in the calcic horizon (node 7) (Figure 4-10G) while in the fluvial soil the water content in the calcic horizon (node 7) exceeds that in the soil (node 6) during short periods of time when soil water contents are at their maximum (Figure 4-10G). At a depth of 300 cm I observe the same pattern of maximum soil water contents at observation nodes located inside the pipe (nodes 12, 13, and 14) and outside the pipe (nodes 15, 16, and 17), respectively (Figure 4-9F, H and Figure 4-10F, H). However, a striking feature is the decreasing soil water content maxima in the calcic horizon at observation nodes located farther away from the interface between soil and calcic horizon (i.e. from node 15 -close to interface- to node 17 -farthest away from interface-). In the eolian soil at approximately day 7000 the maximum water content in the calcic horizon 5 cm away from the interface (node 15) is about 18.3% while at distances of 100 (node 16) and 200 (node 17) cm away from the interface the maximum water contents decrease to about 16.6 and 16.4%. There is also an increasing time delay of peak occurrence when distance to the interface increases. In the fluvial soil the water content changes 5 cm away from the interface (node 15) between soil and calcic horizon are quite similar to those in the eolian soil but at distances of 100 (node 16) and 200 (node 17) cm away from the interface hardly any changes are propagated. Since the hydraulic properties of the calcic horizon in the eolian and fluvial soil are the same, this is more evidence of the complex dynamics between pipe filling and calcic horizon. In addition, the changes of soil water content maxima as a function of distance from the interface at a depth of 300 cm demonstrate that lateral water fluxes across the interface are a common occurrence which adds to the complexity of the flow pattern through pipes.

4.2.4 Episodic Flux Events

The changes of soil water content with depth and with time in the fluvial and eolian soils during the period 1960-1990 (Figures 4-9 and 4-10) clearly demonstrate the propagation of rainfall events through the soil profile. A large rainfall event is followed -at some later time- by an increase of the downward water flux through the bottom of the pipe ($q_{inside\ pipe}$) at depth 300 cm. In this section I explore in which manner episodic precipitation events become episodic recharge events. In order to have all data on the same time scale, I prepared two figures to present $q_{inside\ pipe}$ as mm per day in the fluvial (Figure 4-11) and

Figure 4-11. Downward water flux through pipe bottom ($q_{inside\ pipe}$) in the fluvial soil. The roman numbers refer to recharge events.



eolian soils (Figure 4-12). These figures present more detail of short time changes than Figure 4-8 which presents $q_{inside\ pipe}$ as mm per year. Through the 30 years of simulation I recognize two major water flux events and two minor ones (Figures 4-11 and 4-12). I artificially made annual series of 60 or 90 years by using the daily precipitation data from the period 1960-1989 two or three times in a row. Thus, the first peak in Figures 4-11 or 4-12 around 1960 may have been the result from the precipitation regime in the years 1985-1989. Therefore, this peak will not be taken into consideration.

The four recharge peaks occur in the same periods as four recharge peaks found by Kearns and Hendrickx (1998) in their simulation study using a completely different computer model and different hydraulic soil properties.

All information contained in Figures 4-4, 4-9, 4-10, 4-11, and 4-12 has been summarized in Table 4-3 which presents the day numbers of flux arrival times in both soil profiles without and with pipes, respectively. Clearly, the precipitation events move slower through the fluvial than through the eolian soil. For example, $q_{inside\ pipe}$ peaks during recharge event III (Figures 4.11 and 4.12) at days 7404 and 7307 in, respectively, the fluvial and eolian soil. Since the precipitation event causing these peaks occurred at day 7167, the travel time for the downward water flux has been 237 and 140 days, respectively, in the fluvial and eolian soil. Apparently, downward water fluxes are not only much smaller in the fluvial soil (compare Figures 4-11 and 4-12) but also much slower than in the eolian soil. Table 4-3 also shows that travel times do not differ much between water moving down through the pipe or in a one-dimensional soil profile without calcic horizon. For example, for recharge event III the arrival times through the

Figure 4-12. Downward water flux through pipe bottom ($q_{inside\ pipe}$) in the eolian soil. The roman numbers refer to recharge events.

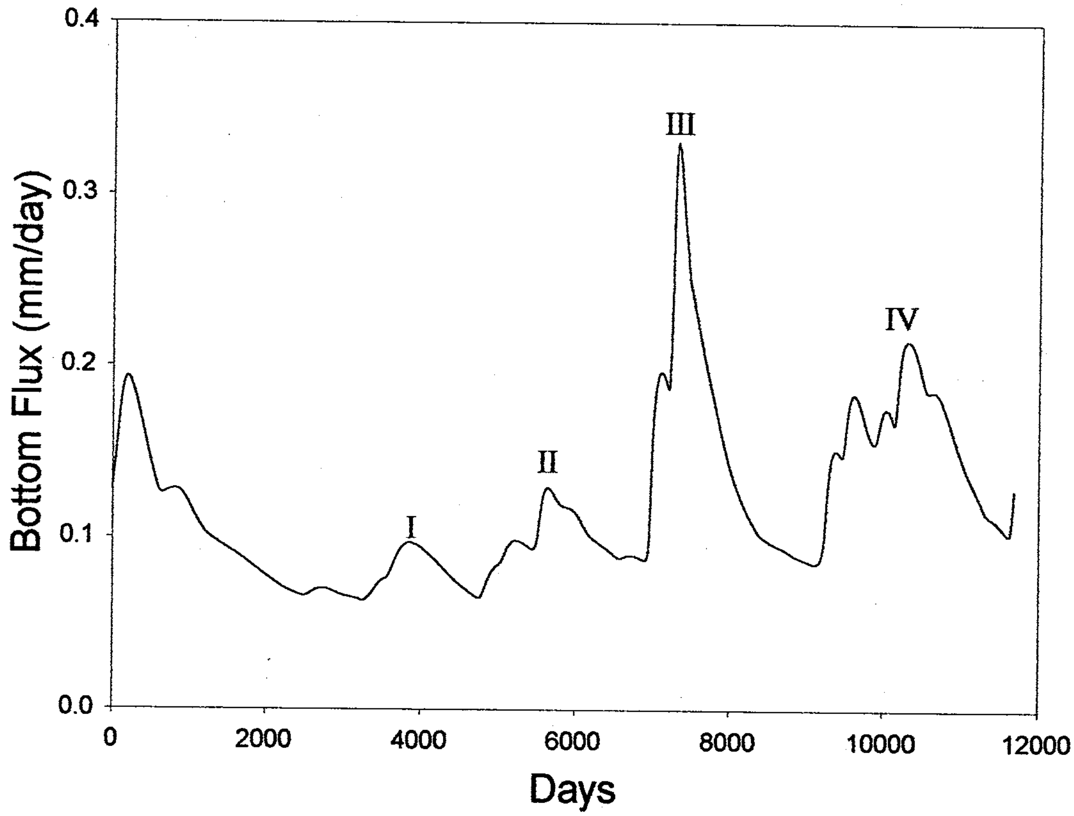


Table 4-3. Arrival times of downward water flux waves during four recharge events in the fluvial and eolian soils.

Eolian

	Water Content Peak Arrival Times (Day)								Bottom Flux Peak (Day)
	Depth (cm)						C H		C H
Event	0	60	120	140	215	300	300	300	300
I	3478	3482	3520	3572	3728	3804	3946	3852	
II	5399	5405	5429	5454	5542	5637	5719	5643	
III	7167	7170	7183	7201	7249	7307	7362	7312	8027
IV	10099	10103	10122	10148	10216	10309	10378	10314	10937

Fluvial

	Water Content Peak Arrival Times (Day)								Bottom Flux Peak (Day)
	Depth (cm)						C H		C H
Event	0	60	120	140	215	300	300	300	300
I	3478	3485	3618	3700	3836	3982	4205	3984	
II	5399	5406	5454	5476	5626	5788	6070	5787	
III	7167	7171	7196	7213	7304	7404	7531	7406	7588
IV	10099	10104	10141	10182	10282	10386	10513	10387	10873

bottom of the pipe versus the one-dimensional profile are 7404 versus 7406 in the fluvial soil and 7307 versus 7312 in the eolian soil.

Of interest is the differences in arrival times through the calcic horizons in the soils with pipes and in the soils without pipes. In the one-dimensional profile without pipes recharge events I and II never make it to a depth of 300 cm. This demonstrates that the calcic horizon is an impediment for ground water recharge. However, the arrival of recharge events III and IV demonstrate that some recharge may occur even through soil profiles with calcic horizons. Arrival times through the one-dimensional soil profile with calcic horizon is substantially delayed compared to those in the calcic horizons close to the pipes. For example, during recharge event III the arrival times in the one-dimensional profile were 8027 versus 7326 in the calcic horizon next to the pipe in the eolian soil. This again points to a complex exchange of lateral fluxes between soil in the pipe and calcic horizon.

In the fluvial soil it takes 504, 389, 237, and 287 days for recharge events I, II, III, and IV to travel from soil surface to depth 300 cm; in the eolian soil it takes, respectively, 326, 238, 140, and 210 days. This shows that the larger downward water fluxes are correlated with smaller travel times.

The simulations conducted in this chapter with the HYDRUS2D model to predict water flow through indurated calcic horizons inside and outside pipes yields quantitative support for my hypothesis, that on surfaces with indurated calcic horizons in arid New Mexico, locations with negligible recharge are intermixed with sites that produce considerable recharge. The simulations also provide evidence that the hydraulic properties of the pipe fillings affect downward fluxes and water movement patterns. Since the simulations are validated by field measurements of chloride profiles and lysimeter annual recharge rates I conclude that my hypothesis should be accepted.

5 - CONCLUSIONS AND RECOMMENDATIONS

The main goal of this study was to test the hypothesis that on surfaces with indurated calcic horizons in arid New Mexico, locations with negligible recharge are intermixed with sites that produce considerable recharge. Evidence has been gathered by (i) field observations of dissolution pipes along a 32 km long trench dug for a gas pipe line on the La Mesa surface in southern New Mexico, (ii) analysis of soil samples taken in vertical profiles inside and outside pipes, and (iii) the implementation of a two-dimensional unsaturated water flow model for evaluation of water flow patterns through indurated calcic horizons and through pipes. My work has led to the following conclusions:

- ❑ The pipes that I have observed at the La Mesa surface in southern New Mexico underlay about 13 to 16% of the area; this percentage is nearly one order of magnitude larger than any number previously reported in the literature.

- ❑ Our field observations and laboratory measurements show widely different chloride and carbonate profiles inside and outside pipes in eolian and fluvial soils. Inside the pipes the chloride concentrations in the soil water and the carbonate concentrations in the soil are approximately two orders of magnitude smaller than outside the pipes in the calcic horizons. This is strong evidence for the occurrence of considerable leaching through the pipes.

- Our simulations of water fluxes through a representative pipe demonstrate not only that pipes do have a pronounced effect on downward water fluxes but also that the hydraulic characteristics of the soil filling and overlaying the pipes determine the magnitude of downward water fluxes through the pipe as well as through the calcic horizon. Pipes increase the areal deep downward flux at depth 300 cm from less than 0.03 mm to 0.1-0.8 mm per year in the fluvial soil and from approximately 3 mm to 4-9 mm per year in the eolian soil. The downward fluxes through the pipe are considerable and amount in the fluvial and eolian filling to, respectively, to 3-20 and 24-95 mm per year.

- The large difference between downward water fluxes outside pipes through the calcic horizon and inside pipes, i.e. from less than 0.03 mm to 3-20 mm per year in the fluvial soil and from 3 mm to 24-95 mm per year supports our research hypothesis that on surfaces with indurated calcic horizons in arid New Mexico locations with negligible downward water fluxes are intermixed with sites that have considerable downward water fluxes.

The results of this investigation have important implications for environmental management strategies. On the one hand the frequent occurrence of dissolution pipes and their enhancement of downward water fluxes make desert sites underlain by indurated calcic horizons very vulnerable for ground water contamination from hazardous materials stored on the desert floor. On the other hand the pipes likely will lead to an overall increase of the regional ground water recharge.

Our research has only addressed the question whether pipes would affect downward water fluxes and their spatial variability over short distances. Future research is needed to evaluate what the extreme spatial variability of downward water fluxes means for ground water recharge as well as for the vulnerability of ground water to contamination. The research should focus on the effects of pipe fillings, pipe dimensions, pipe distances, hydraulic properties of pipe fillings and calcic horizons, the depth of the calcic horizon, and vegetation.

6 - REFERENCES

Allison, G.B., P.G. Cook, S.R. Barnett, G.R. Walker, I.D. Jolly, and M.W. Hughes. 1990. Land clearance and river salinisation in the western Murray Basin, Australia. J. Hydrol. 119:1-20.

Bachman, G.O., and M.N. Machette. 1977. Calcic soils and calcretes in the southern United States. US Geological Survey open-File Report 77-794. 163 p.

Baumhardt, R.L. and R.J. Lascano. 1993. Physical and hydraulic properties of a calcic horizon. Soil Science 155: 368-375

Boers, Th.M. 1994. Rainwater harvesting in arid and semi-arid zones. International Land Reclamation and Improvement Institute (ILRI), Wageningen, The Netherlands; 132 pp.

Bretz, J.H. and L. Horberg. 1949. Caliche in southern New Mexico. Journal of Geology 57: 491-511.

Conover, W.J. and R.L. Iman. 1981. Rank transformations as a bridge between parametric and nonparametric statistics. The Amer. Stat. 35:124.

Eastham, J., P.R. Scott and R.A. Steckis. 1993. Evaluation of *Eucalyptus camaldulensis* (River Gum) and *Chamaecytisus proliferus* (Tagasaste) for salinity control by agroforestry. Land Degradation & Rehabilitation 4:113-122.

Francis, R.E. and R. Aguilar. 1995. Calcium carbonate effects on soil textural class in semiarid wildland soils. Arid soil research and rehabilitation 9:155-165.

Gee, G.W. and D. Hillel. 1988. Groundwater recharge in arid regions: review and critique of estimation methods. Hydrological Processes 2:255-266.

Gee, G.W., P.J. Wierenga, B.J. Andraski, M.H. Young, M.J. Fayer, and M.L. Rockhold. 1994. Variations in water balance and recharge at three western desert sites. Soil Sci. Soc. Am. J. 58:63-72.

Germann, P.F. 1990. Macropores and hydrologic hillslope processes. In: M.G. Anderson & T.P. Burt (eds), *Process studies in hillslope hydrology.* Chapter 10; 327-363.

Gile, L.H. 1961. A classification of ca horizona in the soils of a desert region, Doña Ana County, New Mexico. Soil Science Society of America Proc. 25:52-61.

Gile, L.H. and J.W. Hawley. 1966. Periodic sedimentation and soil formation on an alluvial-fan piedmont in southern New Mexico. Soil Science Society of America Proceedings 30:261-268.

Gile, L.H., J.W. Hawley and R.B. Grossman. 1981. Soils and geomorphology in the basin and range area of southern New Mexico. Guide book to the desert project. New Mexico bureau of mines and mineral resources. Memoir 39. 229 p.

Gile, L.H., F.F. Peterson, and R.B. Grossman. 1966. Morphologic and genetic sequences of carbonate accumulation in desert soils. Soil Science 101:347-360.

Hendrickx, J.M.H. 1990. Determination of hydraulic soil properties. In: M.G. Anderson & T.P. Burt (eds), Process studies in hillslope hydrology. Chapter 3; 43-92.

Hendrickx, J.M.H. and M. Flury. 2001. Uniform and preferential flow mechanisms in the vadose zone. *In*: D.A. Feary (Editor), Conceptual models of flow and transport in the fractured vadose zone, National Research Council, National Academy Press, Washington, D.C. pp. 149-187.

Hendrickx, J. M. H. and G. Walker. 1997 Recharge from precipitation, Chapter 2, *In*: I. Simmers (ed.), Recharge of phreatic aquifers in (semi)-arid areas, Balkema, Rotterdam, The Netherlands.

Hennessy, J.T., R.P. Gibens, J.M. Tromble, and M. Cardenas. 1983. Water properties of caliche. Journal of Range Managment 36 :723-726

Johnson, D.L. 1997. Geomorphological, geoecological, geoarcheological, and surficial mapping study of McGregor Guided Missile Range, Fort Bliss, New Mexico. US Army Corps of Engineers, Fort Worth District. Miscellaneous Report of Investigations, Number 157.

Johnston, C.D. 1987. Preferred water flow and localized recharge in a variable regolith. J. Hydrol. 94:129-142.

Kearns, A.K. and J.M.H. Hendrickx. 1998. Temporal variability of diffuse groundwater recharge in New Mexico. Technical Completion Report No. 309, New Mexico Water Resources Research Institute, New Mexico State University, Las Cruces NM.

Klute, A. and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. Chapter 28 *In*: A. Klute et al. (Eds.), Methods of soil analysis, Part 1, Physical and Mineralogical Methods. Second Edition.

Knox, G.F. 1977. Caliche profile information, Saldanha Bay (South Africa). Sedimentology 24:657-674.

Lattman, L.H. 1977. Weathering of caliche in southern Nevada. *In*: Doehring, D.O. (Ed.), Geomorphology in arid regions. Allen and Unwin, Ltd., London. pp. 221-231.

Lerner, D.N., A.S. Issar and I. Simmers. 1990. Groundwater recharge. A guide to understanding and estimating natural recharge. International contributions to hydrogeology; Vol 8. Internat. Assoc. of Hydrogeologists, Heise, Hannover.

Love, D.W. and W.R. Seager. 1996. Fluvial fans and related basin deposits of the Mimbres drainage. New Mexico Geology 18:81-92.

Machette, N.M., 1985. Calcic soils of the southern Unites States. In Weide, D.L. (Eds). Soil and quaternary geology of the southern United States. Geological Society of America Special Paper 203: 1-22.

Malm, N.R. 1994. Climatic guide, Las Cruces, 1892-1991: 100 years of weather records. Agricultural Experiment Station, Research Report 682, College of Agriculture and Home Economics, New Mexico State University.

Mann, J.F. 1976. Waste water in the vadose zone of arid regions: hydrologic interactions. Ground Water 14:367-373.

Marthaler, H.P., W. Vogelsanger, F. Richard, and P.J. Wierenga. 1983. A pressure transducer for field tensiometers. Soil Sci. Soc. Am. J. 47:624-627.

McGrath, D. A. 1984. Morphological and mineralogical characteristics of indurated caliches of the Llano Estacado. MS thesis. Texas Tech University. 290p.

Mercer, J.W., P.S.C. Rao and I.W. Marine (eds). 1983. Role of unsaturated zone in radioactive and hazardous waste disposal. Ann Arbor Science, Ann Arbor, Michigan, USA.

Meyboom, P. 1966. Unsteady groundwater flow near a willow ring in hummocky moraine. J. Hydrol. 4:38-62.

Nieber, J.L., Ċ.A.S. Tosomeen and B.N. Wilson. 1993. A stochastic-mechanistic model of depression focused recharge. *In*: Y. Eckstein & A. Zaporozec (eds), Hydrogeologic Inventories and Monitoring and Groundwater Modeling. Proc. of Industrial and Agricultural Impacts on the Hydrologic Environment; 207-229.

Osterkamp, W.R. and W.W. Wood. 1987. Playa-lake basins on the southern High Plains of Texas and New Mexico: Part I. Hydrologic, geomorphic, and geologic evidence for their development. Geological Society of America Bulletin 99:215-223.

Phillips, F.M. 1994. Environmental tracers for water movement in desert soils of the American Southwest. Soil Sci. Soc. Am. J. 58:15-24.

Phillips, F.M., J.L. Mattick, T.A. Duval, D. Elmore, and P.W. Kubik. 1988. Chlorine-36 and tritium from nuclear weapons fallout as tracers for long-term liquid and vapor movement in desert soils. Water Resour. Res. 24:1877-1891.

Reeves, C.C. 1976. CALICHE. Origen, classification, morphology and uses. Estacado Books. 233p.

Rockhold, M.L., M.J. Fayer, C.T. Kincaid and G.W. Gee, G.W. 1995. Estimation of natural ground water recharge for the performance assessment of a low-level waste disposal facility at the Hanford site. Pacific Northwest Laboratory, Battelle. PNL-10508/UC-702.

Scanlon, B.R. 1992. Moisture and solute flux along preferred pathways characterized by fissured sediments in desert soils. J. of Contaminant Hydrol. 10:19-46.

Shreve, F and T.D. Mallery. 1932. The relation of caliche to desert plants. Soil Science 35:99-113.

Šimůnek, J., M. Šejna, and M. Th. Van Genuchten. 1999. HYDRUS-2D/MESHGEN-2D code for simulating water flow and solute transport in two-dimensional variably saturated media. IGWMC - TPS 53C, Ver. 2.01, International Ground Water Modeling Center, COlorado School of Mines, CO 80401, USA.

Singer, M. and P. Janitzky (Eds.). 1986. Field and laboratory procedures used in a soil chronosequence study. Bulletin 1648, US Geological Survey, Denver CO.

Stakman, W.P. and B.G. Bishay. 1976. Moisture retention and plasticity of highly calcareous soils. Neth. J. Agric. Sci. 24:43-57.

Stephens, D.B. 1994. A perspective on diffuse natural recharge mechanisms in areas of low precipitation. Soil Sci. Soc. Am. J. 58:40-48.

Stephens, D.B. and R. Knowlton 1986. Soil water movement and recharge through sand at a semi-arid site in New Mexico. Water Resour. Res. 22:881-889.

Winograd, I.J., 1981. Radioactive waste disposal in thick unsaturated zones. Science. 212:1457-1464.

Wood, W.W. and W.E. Sanford. 1995. Chemical and isotopic methods for quantifying groundwater recharge in a regional, semiarid environment. Ground Water 33:458-468.