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Infiltration of Urban Stormwater Runoff to Recharge Groundwater Used for Drinking Water:

A Study of the San Fernando Valley, California

A Group Project submitted in partial satisfaction of the requirements for the degree

of

Master of Environmental Science and Management

by

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. It is a three-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

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ABSTRACT

Our study explored the use of infiltration basins that capture urban stormwater runoff as a means of increasing the reliability of local groundwater resources used for drinking water in the San Fernando Valley of Los Angeles County. We first determined the volume of runoff that could be captured by infiltration basins using a calculation based on empirical studies. Model-based predictions were then used to evaluate the depth of soil necessary to sufficiently reduce stormwater contaminants in three different soil types. Finally, we analyzed the cost-effectiveness of this management option by comparing costs of infiltration basins with the value of recharged groundwater, equivalent to the value of the marginal source of drinking water.

We found that infiltration basins with a surface area of 0.1 acre or 0.5 acre with a depth of two feet or three feet, located in a five-acre drainage area, could capture a volume of stormwater runoff ranging from 0.90 to 1.87 acre-feet per year. Our results indicated that smaller basins are more efficient at capturing runoff than larger basins. Given depths to groundwater ranging between 66 feet and 361 feet, depending on soil type, there was no contamination of groundwater from infiltrated stormwater containing the contaminants that we considered.

However, we determined that infiltration basins are not a cost-effective method of increasing drinking water supplies, as the costs of constructing and maintaining an infiltration basin far exceed the value of the drinking water that it provides. Our cost-effectiveness analysis focused on the value of stormwater infiltration solely as a method of augmenting drinking water supplies. The inclusion of benefits of infiltration as a stormwater management strategy may make this method cost-effective.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF ACRONYMS

ARAR	Applicable or Relevant and Appropriate Requirement
BMP	Best Management Practice
BTEX	Benzene, toluene, ethylbenzene, and xylene
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CWA	Clean Water Act
CWC	California Water Code
DHS	California Department of Health Services
DWR	California Department of Water Resources
EMC	Event Mean Concentration
EPA	United States Environmental Protection Agency
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
LAA	Los Angeles Aqueduct
LACDPW	Los Angeles County Department of Public Works
LADWP	Los Angeles Department of Water and Power
LARWQCB	Los Angeles Regional Water Quality Control Board
MCL	Maximum Contaminant Level
MCLG	Maximum Contaminant Level Goal
MWD	Metropolitan Water District of Southern California
NPDES	National Pollutant Discharge Elimination System
NURP	Nationwide Urban Runoff Program
PAH	Polynuclear Aromatic Hydrocarbon
PRG	Preliminary Remediation Goal
RCRA	Resource Conservation and Recovery Act
SDWA	Safe Drinking Water Act
SUSMP	Standard Urban Stormwater Mitigation Plan
SWP	State Water Project
SWRCB	State Water Resources Control Board
TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
TSCA	Toxic Substances Control Act
ULARA	Upper Los Angeles River Area
USDA	United States Department of Agriculture

INTRODUCTION

The City of Los Angeles has a large population and is located in a semi-arid region with a small amount of annual rainfall. As such, it is without an adequate local source of drinking water. To support its massive growth over the last hundred years, the City of Los Angeles has imported most of its water from the Owens Valley in northern California. The City also buys a small amount from the Metropolitan Water District, which imports water from the Colorado River and the Central Valley. Only 15% of the City's water supply comes from a local source, which is groundwater. The aquifer from which the majority of drinking water is extracted is the San Fernando Groundwater Basin, located in the San Fernando Valley of Los Angeles. Due to political and environmental constraints, imported sources may be inadequate to meet future demand, which is projected to increase by 20% by the year 2020. Enhancing existing groundwater aquifers in Los Angeles would reduce the city's dependence on imported water by allowing more water to come from a local source.

Groundwater is naturally recharged when rain infiltrates the ground and percolates downward. However, the impervious surfaces that cover most of Los Angeles have impeded the infiltration of stormwater and the subsequent recharge of aquifers. Stormwater that does not infiltrate the ground becomes runoff and is usually conveyed to storm drains and then to streams and oceans. As the stormwater moves along the ground, it picks up contaminants that may have negative ecological impacts on aquatic systems. Contaminated stormwater runoff poses a problem because of increasingly strict stormwater quality regulations and the high costs of treatment. One alternative to conveying runoff to storm drains is to divert it to a constructed stormwater infiltration basin, where it can infiltrate, be treated through natural soil processes, and recharge groundwater.

Due to the high demand for drinking water in Los Angeles, the option to use stormwater runoff to recharge groundwater used for drinking water is particularly appealing and could potentially solve two problems: those of contaminated stormwater and inadequate local water supplies. However, there is the possibility that the contaminants in stormwater runoff could adversely affect groundwater if not properly treated by the soil. Soil is generally considered to have the ability to remove contaminants from water, but the appropriateness of this management option depends on both stormwater and site characteristics. Therefore, it is necessary to identify the constraints surrounding this process to ensure that groundwater supplies are not contaminated.

We approached our study of diverting stormwater runoff to an infiltration basin to recharge groundwater used for drinking water by asking three questions:

- What volume of stormwater could be captured by infiltration basins?
- What depth to groundwater is necessary to sufficiently reduce contaminant concentrations as stormwater infiltrates the soil?
- Are infiltration basins a cost-effective method of recharging groundwater used for drinking water?

Our report begins by describing the San Fernando Valley of Los Angeles County and discussing the groundwater basins, soils, land use distribution, and climate of this area. We present the demand for drinking water in the Los Angeles region and the sources of drinking water used to meet demand, including local groundwater. We discuss federal regulation of groundwater as well as groundwater management in California and groundwater rights in Los Angeles. We then discuss the generation of stormwater runoff and explain the typical contaminants that it contains. We also clarify the concept of an infiltration basin and describe current infiltration systems implemented in Los Angeles County.

Next, we explain our calculation of the volume of stormwater runoff that can be captured in infiltration basins of varying sizes. Depending on the infiltration rate of the soil upon which the basin is placed, and assuming that runoff is generated from a five-acre drainage area, a basin with a surface area of 0.1 acre and a depth of two feet can capture from 0.90 to 0.96 acre-feet of stormwater runoff; a basin with a surface area of 0.1 acre and a depth of three feet can capture from 1.10 to 1.18 acre-feet; a basin with a surface area of 0.5 acre and a depth of two feet can capture from 1.71 to 1.87 acre-feet; and a basin with a surface area of 0.5 acre and a depth of three feet can capture 1.87 acre-feet.

We then put forward the proportion of typical concentrations of contaminants removed as stormwater infiltrates three different soil types: silty clay loam, sandy loam, and clay loam. Based on these proportions, we conclude that, in order to meet the Maximum Contaminant Levels set for drinking water, depths to groundwater of 66 feet, 361 feet, and 131 feet in these three soil types, respectively, are required in order for the contaminant concentrations to be adequately reduced while infiltrating the soil.

Finally, we present the cost-effectiveness of stormwater infiltration basins constructed to recharge groundwater used for drinking water. We compare the costs of infiltration basins to the value of the marginal source of drinking water, provided by the Metropolitan Water District to the City of Los Angeles, and conclude that infiltration basins are not a cost-effective method of increasing drinking water supplies.

The results of our study will be presented to the Los Angeles and San Gabriel Rivers Watershed Council, a stakeholder group whose mission is to preserve, restore, and enhance the beneficial uses of the two watersheds for which it is named. The Watershed Council, in conjunction with the United States Bureau of Reclamation, will utilize our results as preliminary findings for a five-year study of groundwater recharge by stormwater runoff.

BACKGROUND

AREA OF STUDY

The San Fernando Groundwater Basin in the San Fernando Valley of Los Angeles County was chosen as our area of study because it is a significant source of drinking water for the City of Los Angeles and the largest aquifer in the Los Angeles region.

THE CITY OF LOS ANGELES AND THE SAN FERNANDO VALLEY

With approximately 3.8 million people in its 465-square mile area, the City of Los Angeles is one of the most populous urban regions in the United States. The San Fernando Valley is located in the center of the City of Los Angeles. The Valley and its surrounding hills and mountains make up the Upper Los Angeles River Area (ULARA), which constitutes the entire watershed for the Los Angeles River (Blomquist, 1992). The ULARA is bordered on the north and northwest by the Santa Susana Mountains; on the north and northeast by the San Gabriel Mountains; on the east by the Verdugo Mountains; on the west by the Simi Hills; and on the south by the Santa Monica Mountains.

The ULARA is located almost entirely within Los Angeles County; the Los Angeles-Ventura County line runs through the far western hills of the watershed (see Figure 1). The region encompasses 328,500 acres (513 square miles), consisting of 122,800 acres (192 square miles) of valley fill (i.e., groundwater basins) and 205,700 acres (321 square miles) of hills and mountains. Cities and communities within this watershed include Hidden Hills, Calabasas, San Fernando, Universal City, Burbank, Glendale, La Crescenta, and La Canada-Flintridge (see Figure 2).

GROUNDWATER BASINS IN THE SAN FERNANDO VALLEY

Approximately 90% of groundwater extracted in Los Angeles comes from the ULARA, while the remainder comes from the Central and West[1] Basins, both of which are outside the ULARA. Four distinct groundwater basins make up the ULARA – the San Fernando, Sylmar, Verdugo, and Eagle Rock Groundwater Basins (see Figure 3). The City has groundwater extraction rights in all of these basins except Verdugo Basin. The San Fernando Groundwater Basin is the largest in the ULARA and supplies most of the City's groundwater. The Eagle Rock Basin is the smallest and, as it has no significant native yield, is not used by the City for groundwater supply. These groundwater basins are replenished by the infiltration of

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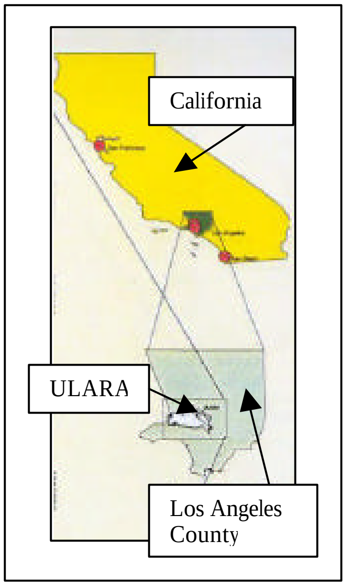
[1] Also referred to as West Coast Basin.

Figure 1: Location of ULARA Within Los Angeles County and California



Source: ULARA Watermaster, 2000.

rainfall, stormwater runoff, and water used within the basin (e.g., for irrigation) (ULARA Watermaster, 2000).

The San Fernando Groundwater Basin is 112,000 acres (175 square miles) in size, making up about 91% of the total valley fill. Its total capacity is estimated at 3.2 million acre-feet (AF)[2] (Blomquist, 1992). The San Fernando Groundwater Basin is bounded on the east and northeast by the San Rafael Hills, Verdugo Mountains, and San Gabriel Mountains; on the north by the San Gabriel Mountains and the eroded south limb of the Little Tujunga Syncline, which separates it from the Sylmar basin; on the northwest and west by the Santa Susana Mountains and Simi Hills; and on the south by the Santa Monica Mountains. The Los Angeles River emerges from the Los Angeles Narrows at the eastern end of the San Fernando Valley, fueled partly by groundwater flowing from east to west in the San Fernando Groundwater Basin (see Figure 4).

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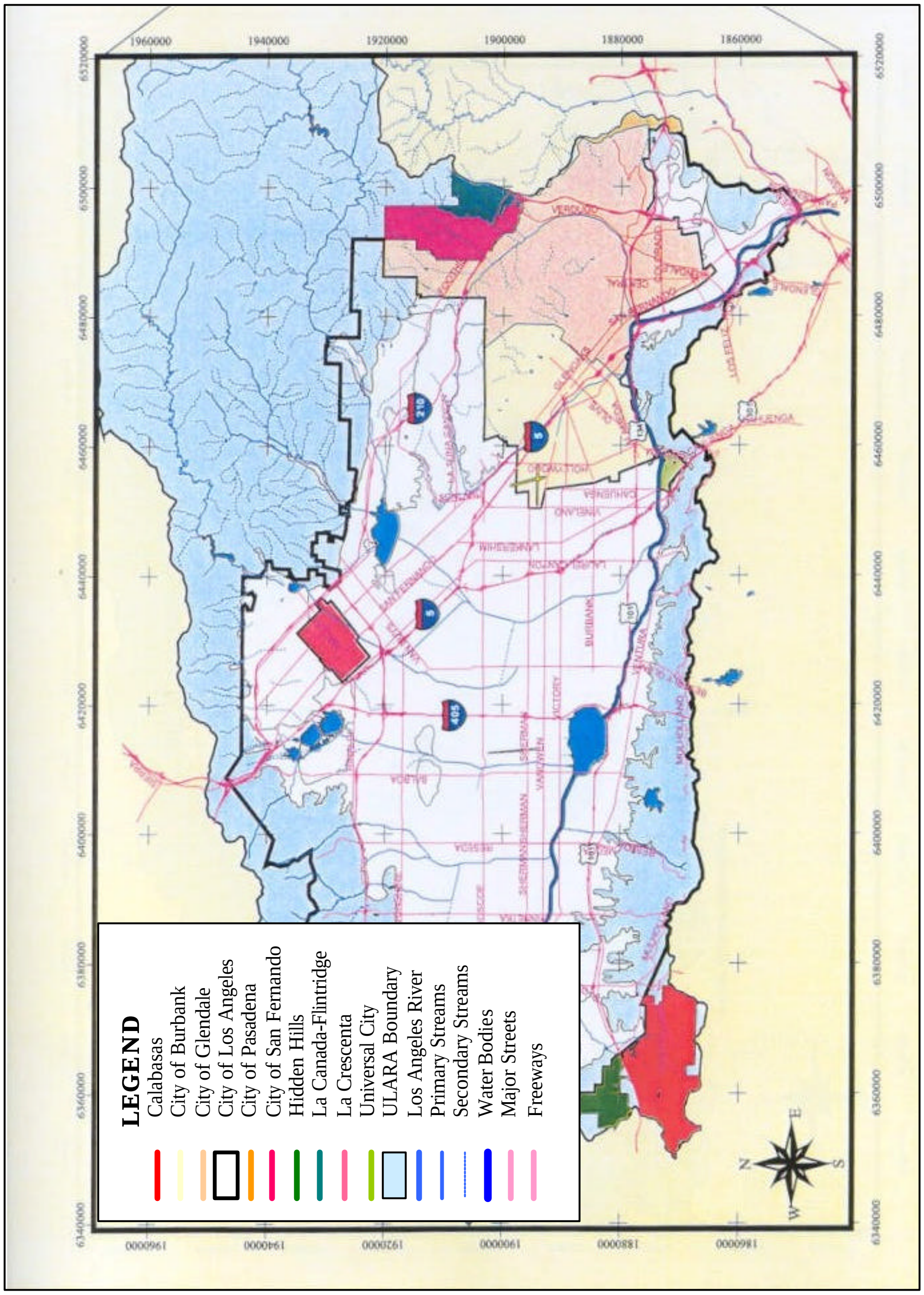
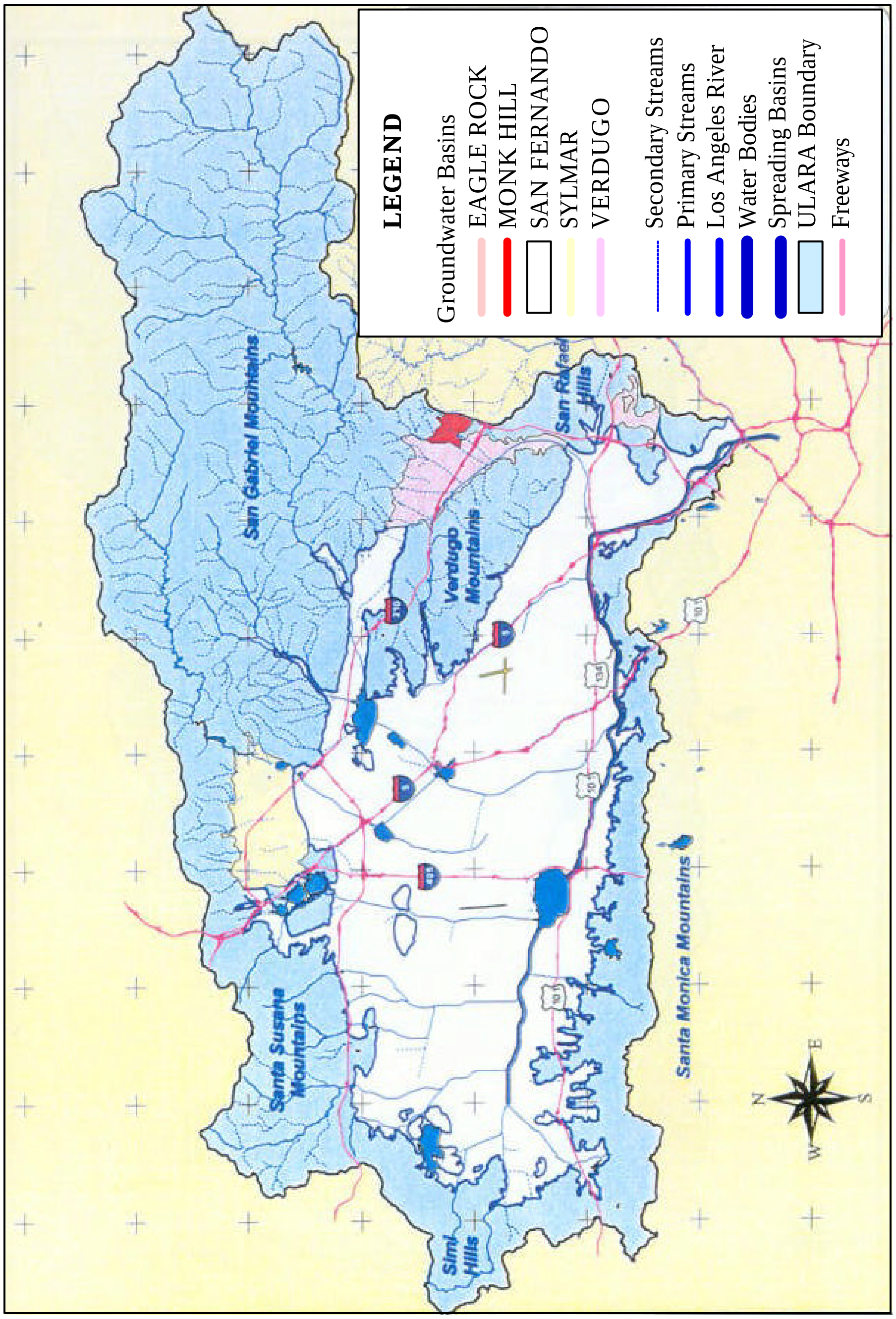
[2] In water resources planning and management, measurements of water are given in units of acre-feet. By definition, one acre-foot is the amount of water that would cover an acre of land to a depth of one foot, which equals 326,000 gallons. An acre-foot of water is about enough to supply one to two typical Southern California families with water to use in and around their homes for a year (LADWP, 2000).

Figure 2: Cities in the ULARA Region



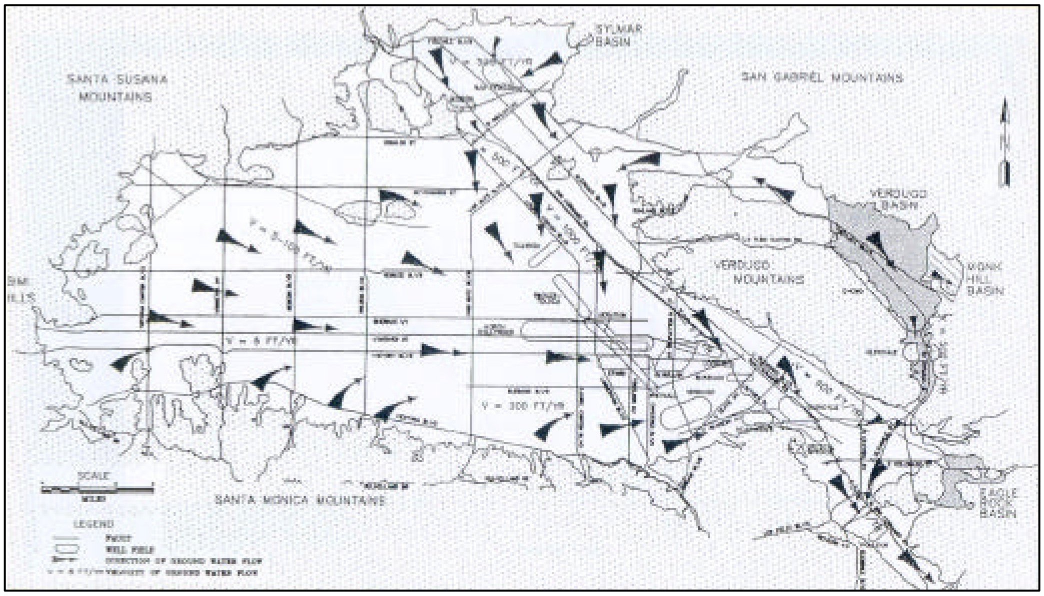
Source: ULARA Watermaster, 2000.

Figure 3: Groundwater Basins in the ULARA Region



Source: ULARA Watermaster, 2000.

Figure 4: Direction of Groundwater Flow in The ULARA

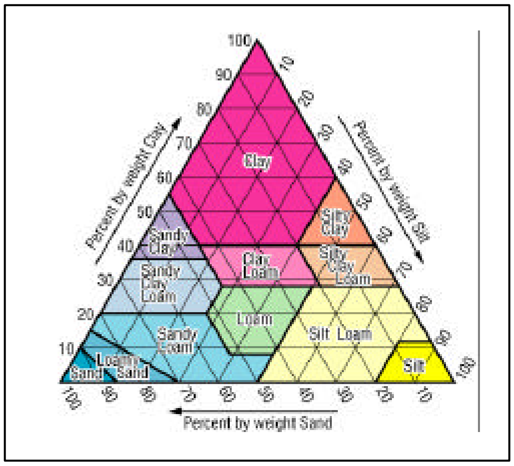


Source: ULARA Watermaster, 2000.

SOILS IN THE SAN FERNANDO VALLEY

There are nine major soil types in the San Fernando Valley. Soils are described by their texture, which is classified according to percent composition by weight of clay, sand, and loam. The United States Department of Agriculture (USDA) has developed a soil texture triangle that can be used to classify soil type (see Figure 5).

Figure 5: USDA Soil Texture Triangle



Source: Earth System Science Center, 1999.

Three types of soils predominate the western San Fernando Valley: San Emigdio-Capistrano (sandy loam), Mocho-Conejo (clay loam), and Balcam-Xerorthents (silty clay loam), making up 21%, 23%, and 29%, respectively, of the soils in the western valley (See Table 1) (USDASCS, 1980). We focused on the western San Fernando Valley because groundwater in the San Fernando Basin flows from west to east. Therefore, water that infiltrates in the western valley has a longer residence time in the basin, providing a longer time period during which it can be extracted for drinking water. In addition, the city of interest – Los Angeles – is located in the western half of the San Fernando Valley, while the Cities of Glendale and Burbank are in the east.

Table 1: Soils in the Western San Fernando Valley Area

Soil Group	**Soil Type**	**Proportion of Survey Area**
Soils on alluvial plains, alluvial fans, and terraces		
Chualar	Sandy loam	5%
Cropley	Clay	4%
Mocho-Conejo	Loam and clay loam	23%
San Emigdio-Capistrano	Fine sandy loam and sandy loam	21%
Soboba-Tujunga	Sand and gravelly loamy sand	2%
Soils on foothills and mountains		
Balcom-Xerorthents	Silty clay loam	29%
Friant-Vista	Sandy loam	3%
Gaviota-Rock outcrop	Sandy loam	6%
Saugus-Soper-Millsholm	Loam and gravelly sandy loam	7%

Source: Derived from USDASCS, 1980

The San Emigdio-Capistrano soil group, or sandy loam soil type, is found throughout the San Fernando Valley and in narrow valleys that extend into the foothills. The soils were created in moderately coarse textured alluvium derived from sedimentary and granitic rock. This group covers 21% of the West San Fernando Valley Area. San Emigdio soils are well drained and consist of stratified sandy loam, coarse sandy loam, and loamy sand. Capistrano soils are well drained and consist of fine sandy loam (USDASCS, 1980).

The Mocho-Conejo soil group, or clay loam soil type, is found on alluvial fans and plains throughout the San Fernando Valley and on fans in small valleys that extend into the foothills. The soils formed in medium textured and moderately fine textured, recent alluvium derived mainly from sedimentary rock. This group covers 23% of the West San Fernando Valley Area. Mocho soils are well drained and consist mainly of loam. Conejo soils are well drained and consist of clay loam (USDASCS, 1980).

The Balcom-Xerorthents soil group, or silty clay loam soil type, is found near the Santa Monica Mountains, Simi Hills, and Santa Susana Mountains. The soils formed in residuum from shale and sandstone. This group covers 29% of the West San Fernando Valley Area. Balcom soils, which make up the majority of this soil group, are well drained and consist of calcareous clay loam and silty clay loam. Xerorthents, which make up a much smaller portion of this soil ground, are disturbed soils that result from excavating, cutting, and filling operations, and properties vary (USDASCS, 1980).

LAND USE DISTRIBUTION

The chief land use in the ULARA is urban or built-up land, although rangeland is a close second (see Table 2). Most of the urban or built-up land occurs in the western half of the region, which is the San Fernando Valley itself, while range land and forest land, the third most prevalent land use, occur in the eastern half, which is mountainous (see Figure 6).

Table 2: Land Use Distribution in ULARA

Land Use	Area (acres)	Percentage of ULARA
Urban or Built-up Land	143,349	44%
Range Land	140,478	43%
Forest Land	30,773	9%
Agricultural Land	6,402	2%
Barren Land	5,732	2%
Water	459	--
Wetland	228	--
Unclassified	4	--
Total	327,425	--

Source: EPA, 1999a.

The urban or built-up land use category can be further broken down into residential, commercial, and other urban uses. Of these, residential use is the most prevalent, constituting over two-thirds of the urban or built-up land use category (see Table 3).

CLIMATE OF THE LOS ANGELES REGION

The Los Angeles region is characterized by a Mediterranean climate; summer months are usually dry with little or no rainfall, and most of the precipitation occurs between the months of November and April. Average annual precipitation is typically around 15 inches, although it varies from six inches in dry years to 24 inches in wet years. Droughts are common. In the coastal areas of Los Angeles,

Table 3: Type of Urban or Built-Up Land in ULARA

Type of Urban or Built-up Land Use	Area (acres)	Percentage of Urban or Built-up Land Use Category
Residential	98,911	69%
Commercial	18,635	13%
Urban	25,803	18%
Total	143,349	100%

Source: EPA, 1999a.

temperatures are generally moderate, with warm days and cool nights. In the inland valleys, temperatures fluctuate between greater extremes, as winds from the desert in the late summer often cause temperatures to rise to over 100 degrees Fahrenheit.

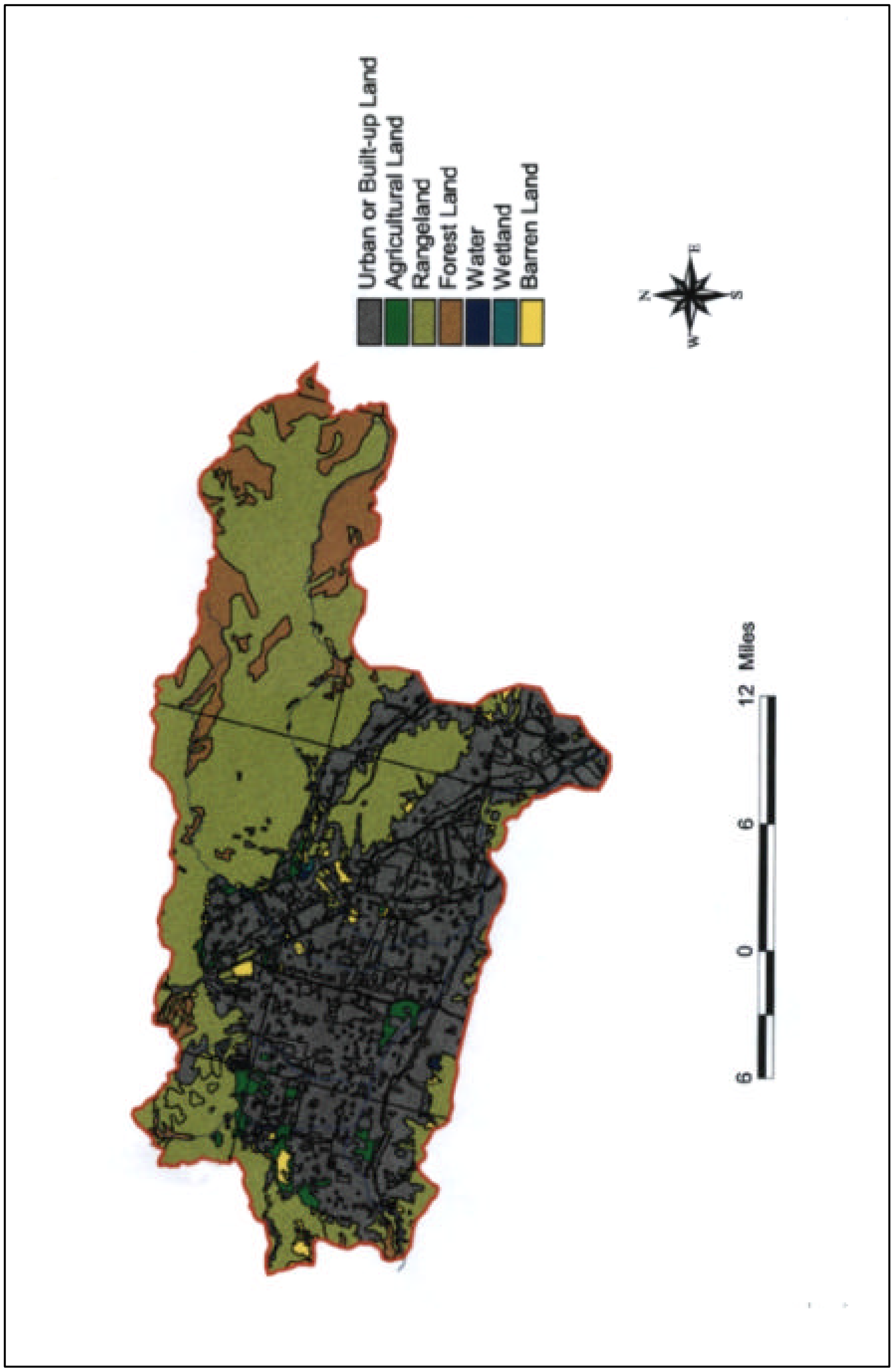
DEMAND FOR AND SUPPLY OF DRINKING WATER

The average per capita consumption of water by Los Angeles residents is 135 gallons per day (LADWP, 1996), with annual water consumption in the City equaling about 660,000 AF (LADWP, 2000). The City's population is estimated to reach more than 4.8 million by the year 2020. By that time, water demand is projected to grow to between 750,000 to 800,000 AF per year, a 20% increase over present demand (LADWP, 2000). The Metropolitan Water District of Southern California (MWD) predicts that current water supplies imported to southern California will be sufficient to meet demand only for the next ten to fifteen years. Beyond that, an additional 300,000 AF will be needed annually (MWD, 1998).

The City of Los Angeles utilizes several sources of water. The Los Angeles Aqueduct (LAA) system, which imports snowmelt, surface runoff, and pumped groundwater from the Owens Valley and Mono Basin to the City, has a total capacity of about 560,000 AF per year. Since 1970, it has supplied an average of 400,000 AF of water annually, meeting about two-thirds of the City's water needs. However, because of concerns over environmental conditions in Owens Valley and Mono Basin, the California Department of Water Resources (DWR) predicts that water imported through the LAA will be reduced to between 300,000 AF and 350,000 AF per year (DWR, 1999a), serving the City with only half of its water needs.

Los Angeles also purchases water from MWD, which imports water from the Colorado River through the Colorado River Aqueduct, as well as from the Sacramento-San Joaquin Bay-Delta in northern California through the California Aqueduct, which is part of the State Water Project (SWP). MWD sells this water to its member agencies, including the City of Los Angeles. About 20% of Los Angeles's annual water needs, or 125,000 AF, are purchased from MWD (MWD, 2001).

Figure 6: Land Use Distribution in the ULARA

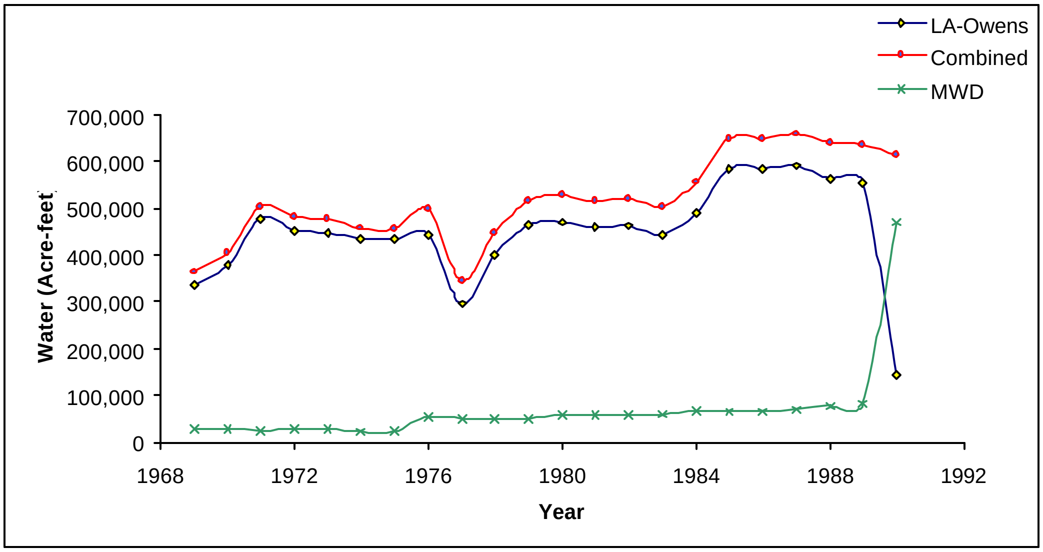


Source: EPA, 1999a.

As demand for water in Los Angeles increases, supply from the Owens Valley decreases, and droughts reoccur, supplemental water purchases from MWD will continue to increase. It is projected that by 2015, the City will increase its reliance on MWD to total approximately 25% of its water supply during normal water years and as much as 45% during dry years. By 2020, MWD will most likely be providing nearly 300,000 AF annually to the City. Water purchases from MWD are largely dependent on water supply conditions from the Eastern Sierra Nevada, which determine how much water the City's aqueducts can deliver to Los Angeles. Wet conditions in the Eastern Sierra Nevada enable more water deliveries from the LAA and less reliance on MWD. Conversely, dry conditions in the Eastern Sierra Nevada result in less LAA deliveries and more reliance on MWD (MWD, 2001).

Figure 7 shows the volume of water imported to Los Angeles between 1969 and 1990 both through the Los Angeles Aqueduct (represented in the graph by "LA-Owens") and from MWD. Complete data are presented in Appendix A. LAA imports sharply declined from 1989 to 1990, while MWD imports increased correspondingly. This point marked the beginning of a drought period that seriously impacted surface water supplies in the Owens Valley. The imports from the north were dramatically reduced, necessitating an increase in deliveries from MWD, particularly from the Colorado River.

Figure 7: Water Imported Into ULARA (1969-1990)

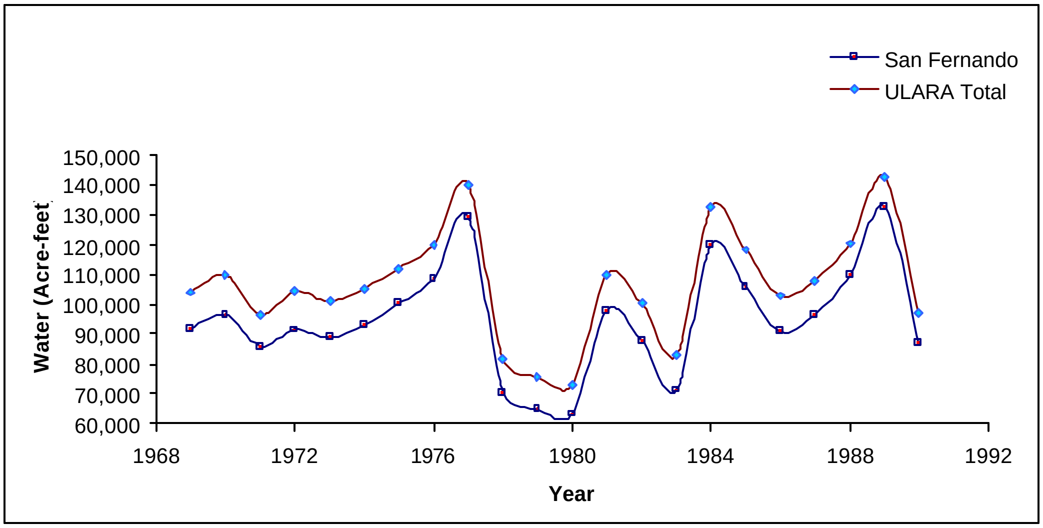


Source: Derived from Blomquist, 1992.

Environmental concerns about the diversion of water from both the Sacramento-San Joaquin Bay-Delta and from the Colorado River have created cause for worry about the reliability of water supplies to Los Angeles. Furthermore, water rights issues involving allocation of water from the Colorado River may also threaten the state's supplies. The 1922 Colorado River Compact allotted 15 million AF per year of the river's water to the seven states through which it flows, including 4.4 million AF annually for California. Should a state not use its allotted share, the surplus water may be reallocated at the Interior Secretary's discretion. Because Arizona and Nevada tend to use less than their full entitlement, California has historically consumed about 800,000 AF more than its annual allocation (MWD, 2001). As Arizona and Nevada continue to grow, their need to reclaim the water allocated to them in 1922 increases, putting pressure on California to reduce its overconsumption. Efforts are currently underway to reduce California's reliance on the Colorado River through conservation, recycling, water storage, and the development of transfer programs (MWD, 2001). Despite the state's excessive consumption of Colorado River water, the City of Los Angeles rarely, if ever, purchases its full entitlement of MWD water (Mackowski, 2001).

The remaining 15% of the City's water needs are provided by local groundwater aquifers (LADWP, 1996), including the San Fernando, Sylmar, Central, and West Groundwater Basins. The San Fernando Groundwater Basin is the largest, providing water to approximately 500,000 Los Angeles residents in the metropolitan area. For the last few decades, the City has extracted about 95,000 AF annually from its groundwater basins (see Figure 8) and has rights to extract up to 110,000 AF during a typical year. Complete data are presented in Appendix B.

Figure 8: ULARA Groundwater Extractions (1969-1990)



Source: Derived from Blomquist, 1992.

In addition to supplying the annual water needs of the City, the San Fernando Groundwater Basin holds large quantities of stored water that can be extracted during droughts and replenished during years of surplus water supply. This storage of groundwater is becoming increasingly important in the City's water management structure. The coordinated use of groundwater and surface water to provide the City with increased reliability during dry years is known as conjunctive use. During wet years, the use of groundwater is limited (thus allowing groundwater levels to recover and storage credits to accumulate), but use is maximized during droughts when surface water imports are reduced. In the San Fernando Groundwater Basin, conjunctive use is essential to ensuring a reliable water supply for the City by providing a reserve for drought and emergency use.

The basin stores enough water to supply about one million people for two years during a drought. Large-scale spreading grounds are used to infiltrate into the basin water from the Los Angeles River and local creeks, in addition to surplus water from the LAA and MWD and treated wastewater (LADWP, 1996; ULARA Watermaster, 2000). Long-term annual supply in the San Fernando Groundwater Basin is projected to increase from 110,000 AF to 152,000 AF by 2015, largely as a result of the continuing operation and increasing capacity of spreading projects using reclaimed water for groundwater recharge and storage. As of June 1996, approximately 300,000 AF existed in storage in the San Fernando Groundwater Basin (LADWP, 1996).

GROUNDWATER MANAGEMENT

Given the local or regional scale of most groundwater basins and the differences in groundwater usage among states, comprehensive federal oversight of groundwater use and management is challenging. Although there are federal laws that allow for indirect federal regulation of some aspects of groundwater use and management, states have been left to develop their own policies of groundwater use and management.

FEDERAL REGULATIONS

There is no single federal groundwater statute that comprehensively addresses either groundwater quality protection or groundwater use and management (Benjamin and Belluck, 1994). However, provisions for groundwater quality protection do exist within some federal acts and regulations designed to address broader issues. The United States Environmental Protection Agency (EPA) is responsible for the implementation and oversight of six federal statutes that contain some language on groundwater protection, although most of them target remediation and cleanup rather than prevention of contamination. These statutes include the Clean Water Act (CWA); the Safe Drinking Water Act (SDWA); the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); the Resource Conservation and Recovery Act (RCRA); the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA); and the Toxic Substances Control Act (TSCA).

The CWA protects groundwater that is hydrologically connected to surface water systems by placing water quality requirements on the surface water. It also requires non-point source pollution prevention strategies to be developed, which can also protect groundwater quality. The SDWA identifies public drinking water standards and includes groundwater protection programs such as the Sole-Source Aquifer program, Underground Injection Control program, and the Wellhead Protection program. CERCLA focuses primarily on the remediation of contaminated groundwater sites, while RCRA focuses on preventing release of contaminants to groundwater aquifers through management standards and cleanup requirements. This act is instrumental in preventing groundwater contamination through solid and hazardous waste disposal. FIFRA and TSCA indirectly prevent groundwater contamination by regulating the use of pesticides on the surface through registration requirements and regulating the introduction or unrestricted use of new chemicals, respectively (Benjamin and Belluck, 1994).

GROUNDWATER MANAGEMENT IN CALIFORNIA

Unified state oversight of groundwater use is lacking in California. The California Legislature has consistently approached groundwater management law, particularly groundwater rights, with a “hands-off policy,” and very few statutes regulating groundwater rights have been adopted (Blomquist, 1988). Instead, groundwater management in California is a local responsibility assigned by a number of court decisions and falls under the authority of the California Water Code (CWC), a body of state laws governing water supplies and resources. Several state and regional agencies have some authority over groundwater quality management and, as such, may play a role in the implementation of groundwater recharge projects (see Table 4).

Under present law, there are six methods by which to manage groundwater; management approaches may include one or more of these methods (DWR, 1999b). The first management method is through overlying property rights that allow anyone in California to build a well on their property in order to extract their correlative share of groundwater, which is not defined until the basin is adjudicated. Even though this is not a coordinated method of groundwater management, it has still been defined as such.

Second, in some parts of California, special legislation has been enacted to form groundwater management districts or water management agencies that may enact ordinances to limit or regulate groundwater extraction. Nine water management agencies in California acquired authority in this manner, and three acquired similar authority through amendments to the CWC.

Table 4: Agencies Addressing Groundwater Quality in California

Activity Affecting Groundwater Quality	**Agencies that Regulate These Activities**						
	State					**Local**	**Federal**
	SWRCB RWQCB	DTSC	DHS	DWR	DOC	CCSD	EPA
Surface impoundments	X	X		X		X	X
Groundwater recharge	X		X				
Water reclamation and recharge	X			X	X	X	

SWRCB	State Water Resources Control Board
RWQCBs	Regional Water Quality Control Board
DTSC	Department of Toxic Substances Control
DHS	Department of Health Services
DWR	Department of Water Resources
DOC	Department of Conservation
CCSDs	Counties, Cities, and Special Districts
EPA	United States Environmental Protection Agency

Source: Derived from Bachman, 1997.

Alternatively, twenty-two types of districts or local agencies are identified in the CWC as having specific statutory provisions to manage surface water. Some of these agencies also have statutory authority to manage groundwater, although not all of them have done so.

Fourth, the CWC provides procedures for an existing local agency to develop a groundwater management plan. This gives the agency the powers of a water replenishment district, allowing it to raise revenue to pay for management of the basin. One hundred forty-nine agencies have adopted groundwater management plans in accordance with these procedures, while others are in the process of doing so.

In addition, cities and counties are also able to adopt ordinances to manage groundwater. Several counties in the state now have such management ordinances, although the nature and extent of the regulatory power of cities and counties to control groundwater is presently uncertain.

The sixth method of groundwater management currently permitted in California is adjudication, which results from a lawsuit brought to trial to determine water rights (e.g., *Los Angeles vs. San Fernando*). The court determines who will be able to extract groundwater and what quantity may be extracted, and it appoints a Watermaster to ensure that the basin is managed in accordance with the court's decree. There are sixteen adjudicated groundwater basins in California, including the

San Fernando Groundwater Basin. In agreement with the 1979 *Los Angeles vs. San Fernando* decision, the ULARA has a court-appointed Watermaster, who is also an employee of the Los Angeles Department of Water and Power (LADWP), to manage the complex appropriation of its groundwater to user cities and agencies.

GROUNDWATER RIGHTS IN LOS ANGELES

The right of the City of Los Angeles to groundwater is a "pueblo right" granted in 1781, when Los Angeles was a pueblo settlement of the King of Spain (Blomquist, 1988). Under this right, the small pueblo of forty-six people – that eventually evolved into the highly populated 465-square mile City of Los Angeles – could use as much water as it needed from the Los Angeles River, along which it was located. Because the San Fernando Groundwater Basin is part of the Los Angeles River watershed, the pueblo right included that groundwater, too. Courts have upheld this right through the majority of cases brought either by or against Los Angeles in a series of litigation that began in 1933 and continued until the 1979 San Fernando decision permanently upheld the pueblo right of the City.

The 1979 San Fernando judgment produced an apportionment of the San Fernando Groundwater Basin waters among the cities of Los Angeles, Glendale, Burbank, and San Fernando. The Watermaster oversees parties' extractions and tracks each party's rights to native groundwater, import return water, and stored waters in the groundwater basin. The City of Los Angeles has pueblo rights to the entire native safe yield of the San Fernando Groundwater Basin (Blomquist, 1992); no other party may pump from the native waters of the Basin. Each of the four cities also has rights to a percentage of their import return flows in the San Fernando Groundwater Basin – that is, the amount of water that recharges the groundwater basin after being imported to the Valley from the LAA or MWD. Los Angeles can receive credit for and pump 20.8% of the water it imports into the Valley; Glendale, 20%; Burbank, 20%; and San Fernando, 26.3% (Blomquist, 1992). Import return flows that are not pumped in a given year by any of the cities can be accumulated as credit and pumped later when needed. Because Los Angeles has rights to all of the water that normally recharges the Los Angeles River via runoff from precipitation, any water that is recharged purposely in the Valley also belongs to Los Angeles.

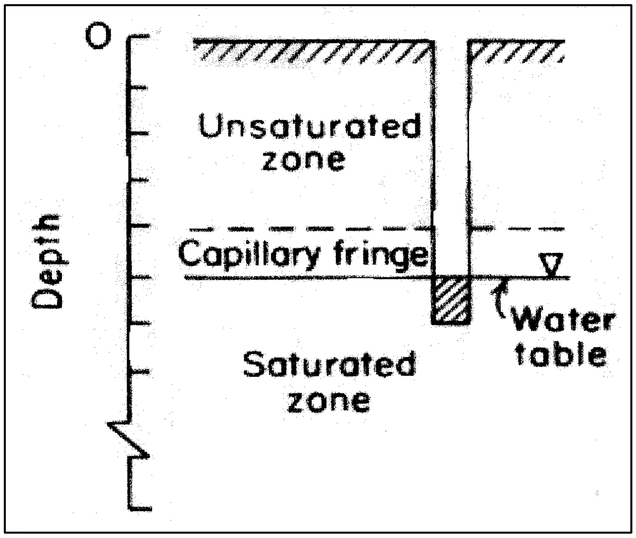
STORMWATER RUNOFF AND INFILTRATION BASINS

GENERATION OF STORMWATER RUNOFF

Infiltration is the movement of water into the soil. As rain falls, water percolates through the soil and fills the spaces (pores) between soil particles. Capillary forces retain some of this water, maintaining the soil moisture content. When soil pores are filled to capacity, infiltration may occur, and water flows downward into the soil by the force of gravity. The rate at which infiltration takes place depends on the texture and porosity (amount of pores) of the soil, which determine the soil's permeability. After water infiltrates, it moves through the unsaturated zone, or vadose zone, and may reach groundwater, which is defined as "subsurface water that occurs beneath the water table in soils and geologic formations that are fully saturated" (Freeze & Cherry, 1979).

Groundwater recharge is "the entry into the saturated zone of water made available at the water table surface, together with the associated flow away from the water table within the saturated zone" (Freeze & Cherry, 1979). The water table is the boundary between the unsaturated zone and the saturated zone, although this boundary is blurred by the presence of a saturated capillary fringe (see Figure 9). The depth of the water table, or distance to groundwater, varies depending on many factors, including amount of groundwater recharge, evapotranspiration, and flow of groundwater into streams (Freeze & Cherry, 1979).

Figure 9: Saturated and Unsaturated Zones



Source: Freeze and Cherry, 1979.

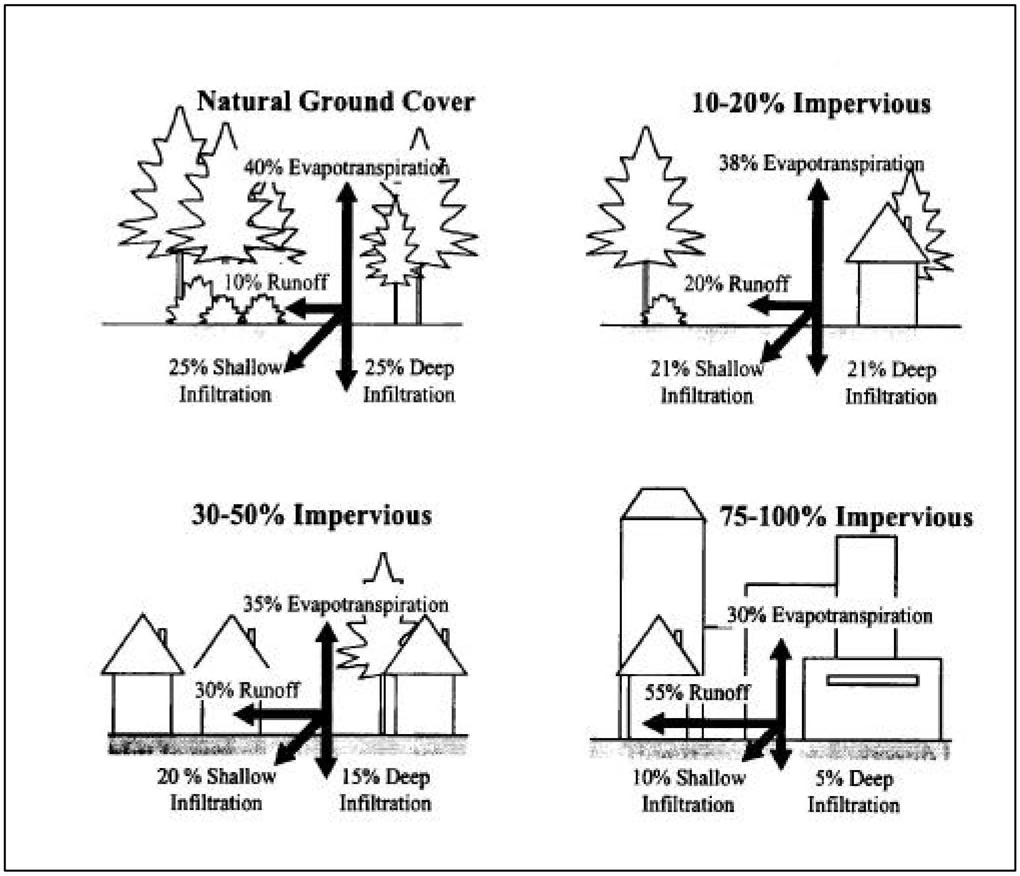
Stormwater runoff occurs when rainfall intensity exceeds the infiltration rate of the surface on which raindrops land. When this happens, water will become runoff by ponding on the surface, flowing over the land, and traveling down slope. The traditional method of managing stormwater runoff in cities has been to construct a network of catch basins and storm drains to rapidly and efficiently move it away from the urbanized area into receiving streams that eventually reach the ocean. These types of storm drainage infrastructures were developed to limit nuisance and local floods caused by large volumes of stormwater runoff (Dallman and Piechota, 1999). In addition to entering streams as point sources after being conveyed through storm systems, stormwater runoff can enter streams as a non-point source from parking lots, highways, open land, rangeland, residential areas, and commercial areas (EPA, 1999b).

Water that moves over land as stormwater runoff does not infiltrate the soil and, therefore, will not recharge groundwater. Because stormwater runoff occurs when rain cannot infiltrate a surface, its generation is affected by the extent of impervious surfaces such as buildings, streets, parking lots, sidewalks, and roofs. Impervious surfaces, as their name implies, have a much lower infiltration capacity than soil and thereby increase both the rate of stormwater runoff generation and the amount of rainfall converted to runoff.

As open land is paved over, the natural hydrology of a watershed is altered. Water that previously ponded and infiltrated the soil, potentially entering groundwater, is now converted directly to stormwater runoff, as it cannot infiltrate. The average runoff volume from subdivisions has been reported to be more than ten times greater than that of typical pre-development agricultural areas (Madison et al., 1979). Because urbanization leads to increased impervious cover as the land is built up, less water infiltrates the ground and more stormwater runoff is generated, resulting in less groundwater recharge (see Figure 10). In the ULARA, the proportion of rainfall that becomes runoff has steadily increased with the increase in amount of impervious surfaces. From the 1930s to the mid-1960s, more than 80% of rainfall infiltrated the ground or evaporated, while less than 20% became runoff. Since then, as the area has become more and more developed, the proportion of rainfall that infiltrates or evaporates has decreased to less than 50%, and the proportion that becomes runoff has increased to over 50% (Dallman and Piechota, 1999).

The larger rates and volumes of runoff associated with urbanization not only decrease the amount of water that may recharge groundwater, but also increase the volumes of water carried by streams. Because the volume of water is proportional to its erosive force, an intensification of stream bank erosion occurs. As water flows over a surface, it picks up and carries different particulate and dissolved elements found on its path. Therefore, stormwater runoff also carries harmful contaminants that may be transported into receiving water bodies (streams, lakes, and oceans), potentially causing detrimental ecological effects.

Figure 10: The Association Between Increased Impervious Cover and Decreased Groundwater Recharge



Source: EPA, 1999b.

CONTAMINATION OF STORMWATER RUNOFF

Several factors influence the quality and quantity of stormwater runoff, including land use and climate (Pitt and McLean, 1986). Land use affects the extent of impervious cover. Commercial and industrial land uses generally have higher impervious cover than residential areas, which may have more land devoted to parks, yards, and other pervious surfaces. Areas of high impervious cover have an associated increase in stormwater runoff. Land use also affects the type of contaminants carried by runoff. Stormwater runoff from lands used for agriculture will contain different contaminants than stormwater runoff from land used for industry, as different chemicals are used on different land uses. Additionally, through its effect on average rainfall intensity and storm duration, the climate of a region affects the concentration of contaminants in stormwater runoff. Areas such as the southwestern United States that have infrequent rainfall generally have runoff with higher concentrations of contaminants. Because it does not rain often, these contaminants may have been building up for long periods of time.

There are seven categories of potentially harmful contaminants associated with urban runoff: solids, organic materials, nutrients, metals, pathogens, oil and grease and hydrocarbons, and synthetic organic chemicals (Terrene Institute, 1994). (Our analysis of contaminant removal focuses on four of these categories: nutrients, metals, pathogens, and synthetic organic chemicals, as discussed in *Removal of Stormwater Contaminants*). These contaminants come from a variety of sources, including residential, industrial, and commercial areas; streets and parking lots; and atmospheric deposition (see Table 5).

Table 5: Sources of Contamination in Urban Stormwater Runoff

Contaminant	Contaminant Sources
Solids	Streets, lawns, driveways, roads, construction activities, atmospheric deposition, drainage channel erosion
Organic Materials	Residential lawns and gardens, commercial landscaping, animal wastes
Nutrients	Lawn fertilizers, atmospheric deposition, automobile exhaust, soil erosion, animal waste, detergents
Metals	Automobiles, bridges, atmospheric deposition, industrial areas, soil erosion, corroding metal surfaces, combustion processes
Pathogens	Lawns, roads, leaky sanitary sewer lines, sanitary sewer cross-connections, animal waste, septic systems
Oil and Grease and Hydrocarbons	Roads, driveways, parking lots, vehicle maintenance areas, gas stations, illicit dumping to storm drains
Synthetic Organic Chemicals	Residential lawns and gardens, roadsides, utility right-of-ways, commercial and industrial landscaped areas, soil wash-off

Source: EPA, 1999b.

Solids include litter, soil particles, sediments, and dust. They cause many water quality, habitat, and aesthetic problems in waterways, such as increased turbidity that results in decreased light penetration and plant growth. Solids that settle out can alter and eventually destroy habitat. Other contaminants, including metals and pathogens, can bind to solids and move with them. Organic materials are problematic because they decompose after runoff enters streams or oceans, demanding large quantities of oxygen as they do so. This may deplete oxygen to levels dangerous to aquatic life.

Primary nutrients are compounds or constituents that contain nitrogen, phosphorus, and other elements essential for plant growth. Nitrogen and phosphorus are the nutrients most commonly tested for and are found in several forms in stormwater runoff. Ammonia (NH_3) is the nitrogen form that is most toxic to aquatic life. Inorganic forms of nitrogen are nitrate (NO_3^-) and nitrite (NO_2^-), although little nitrite is found in stormwater runoff. Organic and ammonia nitrogen forms are measured by total Kjeldahl nitrogen (TKN). Most phosphate is present in stormwater as orthophosphate (HPO_4^-), the soluble and most biologically available form. Total phosphorus measures both soluble and insoluble forms. Excess nutrients in a water body can increase primary biological activity, resulting in an excessive growth of algae that leads to eutrophic conditions. When these algae die and decompose, they can further deplete dissolved oxygen levels.

Metals such as copper, lead, and zinc may be either dissolved or bound to sediments. They can be found in concentrations high enough to impair beneficial uses and cause acute and chronic toxic impacts for aquatic life. Pathogens are disease-causing organisms that present a potential human health threat when stormwater is discharged to recreational waters. The presence of harmful pathogens in stormwater is evaluated by the presence of indicator organisms such as fecal coliform bacteria or fecal streptococcus. However, few analyses of specific pathogenic microorganisms are made (NRC, 1994).

Oil and grease and hydrocarbons contain compounds that cause acute toxicity, such as the benzene, toluene, ethylbenzene, and xylene compounds (BTEX) and polynuclear aromatic hydrocarbons (PAH) found in gasoline. Synthetic organic chemicals include a variety of manufactured compounds such as pesticides, solvents, and household and industrial chemicals. Even though they may be found in low concentrations, these chemicals present a health threat to humans and aquatic life through direct ingestion or accumulation in the food chain.

The most comprehensive study of urban stormwater runoff is the EPA's Nationwide Urban Runoff Program (NURP), conducted between 1978 and 1983 to examine the characteristics of urban stormwater runoff and to determine any difference in contaminant concentration between land uses. In 28 NURP projects, sampling was conducted at 81 sites during over 2,300 storm events to determine median event mean concentrations (EMCs) for ten contaminants (see Table 6). The NURP study also detected concentrations of organic chemicals frequently found in stormwater runoff; these chemicals will be discussed further in *Removal of Stormwater Contaminants*.

Table 6: Median Event Mean Concentrations for Different Land Uses

Contaminant	Units	Land Use			
		Residential	Mixed	Commercial	Open Space
BOD	mg/L	10	7.8	9.3	---
COD	mg/L	73	65	57	40
TSS	mg/L	101	67	69	70
Total Lead	µg/L	144	114	104	30
Total Copper	µg/L	33	27	29	---
Total Zinc	µg/L	135	154	226	195
Total Kjeldahl Nitrogen	µg/L	1900	1288	1179	965
Nitrate and Nitrite	µg/L	736	558	572	543
Total Phosphorus	µg/L	383	263	201	121
Soluble Phosphorus	µg/L	143	56	80	26

BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
TSS	Total Suspended Solids

Source: Derived from EPA, 1999b.

STORMWATER MANAGEMENT AND REGULATIONS

Historically, stormwater discharges have not been regulated under the Clean Water Act (CWA), the principal law governing pollution of the nation’s surface waters that was first passed in 1972. The CWA established the National Pollutant Discharge Elimination System (NPDES) permit system for point source discharges to receiving waters, but it did not specifically address stormwater discharges.

In 1987, the CWA was amended to require NPDES permits for separate stormwater discharges[3]. In 1990, the EPA issued final regulations specifying a two-phase implementation of stormwater permits. During Phase I, permits must be obtained for all discharges from separate stormwater conveyance systems (storm drains) in municipalities with populations greater than 100,000 people. In addition, states were directed to develop and implement non-point source pollution management programs. In 1999, the EPA published a final rule mandating that municipalities with less than 100,000 people obtain an NPDES stormwater permit.

Amendments to the California Water Code (CWC) authorized California to administer the EPA’s permit program. The state’s nine Regional Water Quality Control Boards (Regional Boards), divisions of the California Environmental Protection Agency’s State Water Resources Control Board (SWRCB), have primary responsibility for implementation and enforcement of the permits. Regional Boards are required to adopt a water quality control plan for their region. This plan is subject

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[3] Stormwater may be conveyed either separately through storm drains or combined with sewage in combined sewer systems.

to approval by the SWRCB and ultimately the EPA. Regional Boards implement the NPDES program by issuing discharge permits after certifying that the discharge will comply with applicable water quality standards (LARWQCB, 2000).

In anticipation of the 1990 regulations, Los Angeles County, in conjunction with 18 cities within the County, applied for and was issued a five-year NPDES permit for urban stormwater runoff discharges. It was issued in advance of the final Federal Regulations to allow for the development of a permit more suited to the County's extensive storm drain system (Lehman, 1994). Because the permit was vague and general, stormwater management programs varied widely from city to city (LACDPW, 2000). The permit was reissued in 1996 after one and a half years of discussions between the Los Angeles Regional Water Quality Control Board (LARWQCB), Los Angeles County, the City of Los Angeles, three smaller cities, and the environmental community. It sought to provide a more coordinated effort by specifying actions that are needed to comply with its requirements.

In 1994, the LARWQCB adopted an updated Water Quality Control Plan for its region, specifying the beneficial uses of receiving waters and providing both narrative and numerical water quality objectives. The Regional Board has implemented a watershed management approach to address water quality protection, emphasizing cooperative relationships between regulators, the regulated community, environmental groups, and other stakeholders in the watershed to achieve the greatest environmental improvements. To implement this approach and facilitate compliance, the County is divided into six watershed management areas. A stormwater management plan is established for each watershed management area and includes requirements with compliance dates to provide specificity and certainty of expectations. It also incorporates provisions that promote customized initiatives, both on a countywide and watershed basis, in developing and implementing cost-effective measures to minimize discharge of contaminants to the receiving water (LARWQCB, 2000).

In 2000, the EPA issued final regulations clarifying regulatory requirements for establishing Total Maximum Daily Loads (TMDLs) of contaminants at a level necessary to ensure that applicable water quality standards can be attained and maintained. States must identify water bodies for which the local wastewater discharge limits are not stringent enough to attain water quality standards, and then they must schedule, based on priority, the establishment of TMDLs for these water bodies over the next ten years. TMDLs include best estimates of pollution from point sources, such as industrial and municipal discharges, and non-point sources, including stormwater runoff. The maximum amount of pollution a water body can receive without violating water quality standards is outlined in TMDLs (Federal Register, 2000).

TMDLs will be enforced through the issuance of NPDES permits that include contaminant limits and a schedule for compliance. Highly contaminated stormwater runoff can cause the limits of a TMDL to be exceeded. It is expensive to install new technology on point sources to further reduce their contaminant releases in order to meet the more stringent standards. Therefore, cities find it more cost-effective to control and treat stormwater runoff, as opposed to requiring new technology on point sources, to reduce contamination entering streams and oceans (Copeland, 1997). Infiltration basins are one method that may be used to manage contaminated stormwater runoff.

INFILTRATION BASINS

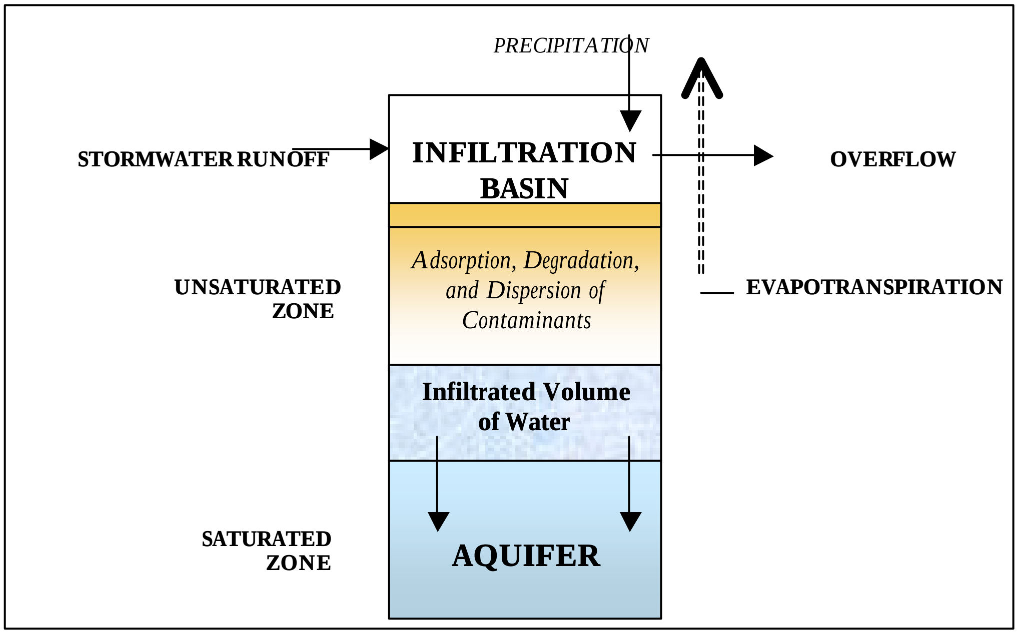
Infiltration basins are impoundments to which incoming stormwater runoff is diverted and allowed to gradually infiltrate the soil toward underlying aquifers (see Figure 11). This concept is presented in Figure 12. Infiltration basins reduce both the peak flow and the total amount of stormwater runoff that is conveyed downstream (Dallman and Piechota, 1999). They consist of open depressions produced by either natural site topography or excavation or may be formed by placing low head dams across natural waterways (O'Hare et al., 1986).

Once stormwater runoff infiltrates the soil, stormwater contaminants may be treated and removed in the subsurface soil through processes such as filtration, adsorption, and degradation, which will be discussed further in *Removal of Stormwater Contaminants*. The greatest environmental concern about the use of infiltration basins is groundwater contamination. Studies have shown that, given the right conditions, many contaminants will be removed by the soil as stormwater infiltrates, causing no adverse impacts on groundwater (EPA, 1999b).

Soil characteristics such as texture and composition determine both the infiltration rate and the proportion of contaminants removed and, as such, are important considerations when placing an infiltration basin. The ideal soil type for stormwater infiltration is one that allows for both complete removal of contaminants and rapid infiltration, preventing long periods of water impoundment. However, this soil type does not exist because the attributes required to reach one goal impede achievement of the other. Coarse-textured soils that transmit water readily have large pores that are inefficient at filtering or adsorbing contaminants. In contrast, fine-textured soils are efficient at contaminant adsorption and filtration but have low permeability and small pores that clog easily. Structured soils containing biological channels (e.g., worm holes, root paths) or cracks are permeable, but water will flow through these large flow paths and bypass the soil matrix. The best choice for soil is therefore a compromise, such as fine sand or sandy loam with relatively little structure (NRC, 1994).

Figure 11: Infiltration Basin

Figure 12: Conceptual Model of an Infiltration Basin



The success of infiltration basins as a method for groundwater recharge depends on both stormwater and site characteristics, including contaminant concentration, depth to groundwater, and antecedent soil moisture of the subsurface soil (EPA, 1999b). Depth to groundwater plays a critical role in the soil's pollution removal efficiency; an increase in depth is an increase in soil available to remove contaminants. Antecedent soil moisture is important since water will infiltrate wetter subsurface soil more quickly than it will drier subsurface soil, giving the contaminants less time to adsorb to soil particles and potentially resulting in less than adequate treatment.

It is also important to have a vadose zone without impeding layers, as restricting layers between the land surface and the aquifer could prevent the infiltrated stormwater from reaching groundwater (Schueler et al., 1992). In addition, infiltration basins must be placed above uncontaminated soil to prevent the infiltrate from collecting these contaminants and transporting them to groundwater (NRC, 1994).

STORMWATER INFILTRATION PROJECTS

The ULARA already contains several "spreading grounds," or large areas in which stormwater runoff or river water (of which a portion is stormwater runoff) is infiltrated. These centralized spreading grounds are designed for concentrating large volumes of water in a few large basins. Pacoima and Hansen Dams, which were originally built for flood control, are now used to regulate stormwater flows and divert them to downstream spreading basins operated by the LACDPW and the City of Los Angeles. There are 3,361 acres of spreading grounds used to recharge groundwater in Los Angeles County, 2,436 acres of which are operated by the LACDPW. During the 1998-99 season, the LACDPW infiltrated a total of 171,987 AF of water: 95,166 AF of stormwater runoff, 28,588 AF of imported water, and 48,233 AF of recycled water. Of this, 14,662 AF of stormwater runoff was infiltrated into the San Fernando Groundwater Basin; no imported water or recycled water was infiltrated into this aquifer. There are no spreading grounds in the other three ULARA groundwater basins (LACDPW, 2000).

The next section presents calculations of the volume of stormwater runoff that could be captured in infiltration basins of a much smaller size. We analyzed capture by infiltration basins with surface areas of 0.1 acre and 0.5 acre, varying basin depth and infiltration rate of the underlying soil.

CAPTURE OF STORMWATER RUNOFF

INTRODUCTION

There are over 3,000 acres of large-scale spreading grounds that infiltrate almost 172,000 AF of water per year in Los Angeles County. Since these spreading grounds are so large, they can capture large volumes of water. However, their size also makes them difficult to place within the highly urbanized Los Angeles County, as there is a lack of large open spaces. Therefore, we determined the volume of stormwater runoff that could be captured from a five-acre drainage area by much smaller infiltration basins that have surface areas of 0.1 acre and 0.5 acre and depths of 2 feet and 3 feet. These smaller sizes allow them to be placed more easily into an area of urban or built-up land use, such as the San Fernando Valley.

The volume of stormwater runoff available for capture is affected by the extent of impervious surface cover, which is related to the land use distribution of the tributary drainage area. The extent of impervious cover affects the amount of stormwater that will infiltrate under natural conditions and, therefore, the amount that will run off and potentially be captured. The volume captured also depends on the frequency and magnitude of precipitation events; in general, more stormwater runoff occurs with larger storms and when soil is still moist from a previous storm.

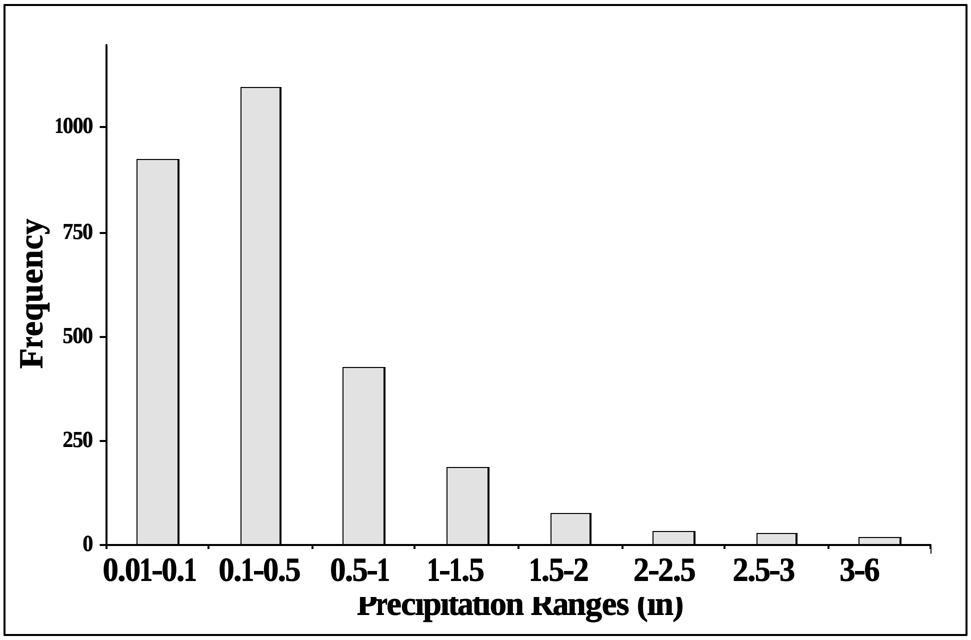
PRECIPITATION DATA

We calculated the amount of stormwater runoff that could be generated from typical rainfall in the ULARA, using precipitation data gathered by the Los Angeles County Department of Public Works (LACDPW) over the last ten years for the city of Northridge, located in the western San Fernando Valley near the city of San Fernando. We assumed that precipitation in Northridge is representative of precipitation in the entire Valley and that ten years is a sufficient timeframe to represent precipitation patterns. Data for this station goes back to 1920. As shown in Figure 13, between 1920 and 2000, the precipitation depths that occur at the highest frequency range from 0.01 inch to 0.5 inch. Very few storm events were large enough to generate over one inch of precipitation.

BASIN SIZE

Given the high urban and built-up land use distribution in the San Fernando Valley, we assumed that stormwater runoff would be captured by relatively small infiltration basins that could more easily be placed into this urban environment. We considered basins with surface areas of 0.1 acre and 0.5 acre. Generally, infiltration basins have a cross-sectional trapezoidal shape (Malaysia Department of Irrigation and Drainage, 2000). Assuming a ratio of 1:0.8 between the surface area and the

Figure 13: Frequency of Days with Precipitation Depths Ranging Between Selected Intervals (1920-2000)



Source: Derived from LACDPW, 2000.

bottom area of the basin, we calculated the maximum capacity of infiltration basins with these two surface areas and depths of 2 feet and 3 feet (see Table 7).

Table 7: Maximum Capacity of Four Infiltration Basins

Surface Area (acres)	Basin Volume (AF)	
	Basin Depth (ft)	
	2	**3**
0.1	0.18	0.27
0.5	0.90	1.35

THE SCS METHOD OF RUNOFF VOLUME ESTIMATION

To calculate the volume of stormwater runoff that could be captured, we used a method developed by the United States Department of Agriculture's Soil Conservation Service (SCS) to estimate the volume of runoff from small agricultural drainage areas. Although this equation, based on empirical studies and a simplified model of runoff and commonly referred to as the SCS Method, was not intended for small, urbanized drainage areas, it may be extended for this application (Dunne and Leopold, 1978). Therefore, it is appropriate for us to use this method in determining the volume of stormwater runoff that could be captured by infiltration basins in the urbanized San Fernando Valley.

The following equation constitutes the SCS Method for runoff estimation:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}, \text{ where}$$

Q = runoff depth (inches)

P = precipitation depth (inches)

I_a = initial abstraction (inches)

S = maximum retention potential (inches) once runoff begins.

The initial abstraction, I_a, is the amount of precipitation that is either infiltrated into the soil or retained in topographical depressions during the initial period of the storm, before runoff begins to occur. The maximum retention potential, S, represents the maximum amount of rainfall the soil can hold once the initial abstraction has been reached and the generation of runoff has begun. Although the initial abstraction is highly variable, the SCS developed an empirical relationship between the initial abstraction (I_a) and the maximum retention potential (S):

$$I_a = 0.2 \cdot S$$

Consequently, the SCS Method can be expressed as:

$$Q = \frac{(P - 0.2S)^2}{(P - 0.8S)}$$

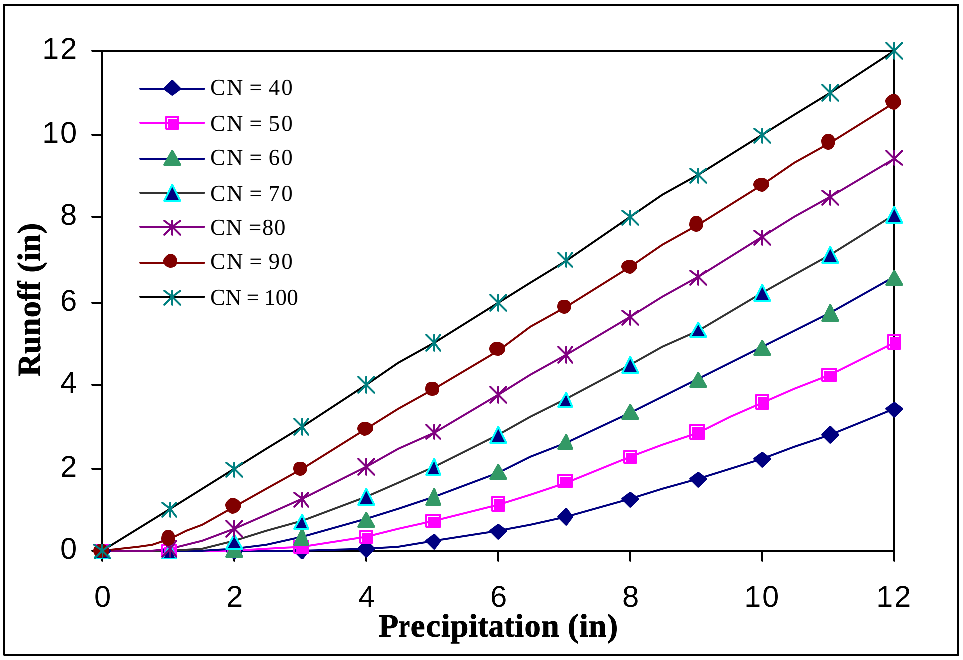
CURVE NUMBER

Once rewritten like this, the SCS Method depends only on estimating the maximum retention potential of the soil, since actual precipitation data is already known. The maximum retention potential, S, is based on three parameters: soil type, which is further classified into soil hydrologic groups based on infiltration rate; surface cover; and antecedent soil moisture, which is affected by the total precipitation occurring within the preceding five days. These three factors are represented by an empirical rating, or curve number (CN). The SCS established an empirical relationship between the maximum retention potential of the soil and the curve number:

$$S = \frac{1000}{CN} - 10$$

Curve numbers have been determined specifically for urban land uses based on the hydrologic soil groups that underlie the built-up land, as well as on the percentage of impervious cover, which affects the amount of precipitation and runoff that may infiltrate the soil (Dunne and Leopold, 1978). An increase in the curve number corresponds to an increase in stormwater runoff that may be generated by the same precipitation event (see Figure 14).

Figure 14: Relationship Between Curve Number and Generation of Stormwater Runoff



Source: Derived from Dunne and Leopold, 1978.

For residential drainage areas, the curve number depends on lot size, which affects the proportion of impervious cover on each lot. Lot size and percent impervious cover are inversely related; that is, a small residential lot is assumed to have a larger percent of impervious surface than a large residential lot. To illustrate, a larger proportion of a small residential lot is covered by the house and driveway than a large residential lot. For example, a $^1/_8$-acre residential lot is assumed to have an impervious cover of 65%. Its curve number ranges between 77 and 92, depending on the soil hydrologic group. However, a one-acre residential lot is assumed to have an impervious cover of only 20%; consequently, its curve number is smaller, ranging between 51 and 84 (Dunne and Leopold, 1978).

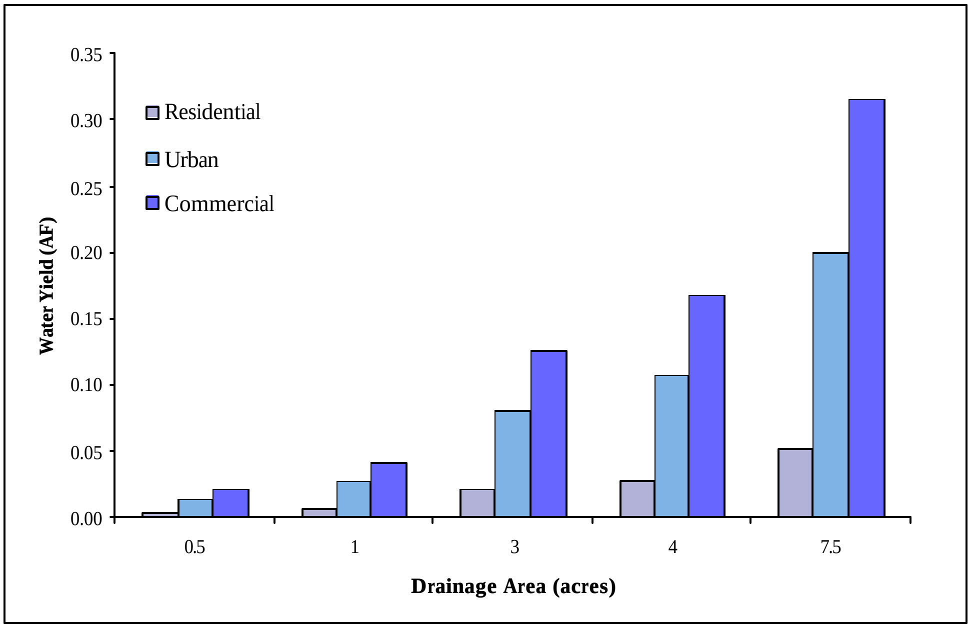
Other urban land uses have curve numbers that are independent of lot size. We assumed that commercial and business areas have an impervious cover of 85%; the curve number ranges from 89 to 95, depending on the soil hydrologic group.

Paved parking lots, roofs and driveways have a curve number of 98 (Dunne and Leopold, 1978).

We made several assumptions about curve numbers in order to assess the volume of stormwater runoff that can be captured by an infiltration basin. Residential lots were assumed to be ½ acre in size with 25% impervious cover and a curve number of 80. This land use is characteristic of suburban developments that have relatively large lots and some pervious surfaces, such as yards and neighborhood parks. Commercial lots, representing areas with small businesses and shops, were assumed to have 85% impervious cover and a curve number of 92. Urban lots were assumed to be $^{1}/_{8}$ acre in size with 65% impervious cover and a curve number of 90. Urban land use represents areas that contain both commercial and residential land uses, although these residential lots are much smaller and mostly covered by impervious surfaces.

Since residential, commercial, and urban land uses have different curve numbers, the amount of stormwater runoff generated from each will vary. The amount of runoff also varies with the drainage area; larger drainage areas will generate relatively more runoff than smaller drainage areas under the same conditions. Figure 15 shows the dependence of volume of stormwater runoff on land use and size of drainage area. We assumed that infiltration basins captured stormwater runoff from a five-acre drainage area, as they are most effective for drainage areas of this size or smaller (CDOT, 2000).

Figure 15: Runoff Volume from Different Land Uses Located on Drainage Areas of Different Sizes



THE EFFECT OF ANTECEDENT SOIL MOISTURE

The amount of runoff generated by a storm event is influenced by the initial moisture conditions of the soil. Soils with high antecedent soil moisture will yield runoff more rapidly than drier soils, since the initial abstraction, I_a, is less and the retention capacity is reached faster.

Antecedent soil moisture is dependent on the magnitude of and time interval between storm events and should be accounted for when determining the curve number. Curve numbers can be adjusted for antecedent soil moisture content based on the amount of precipitation that has fallen during the five preceding days. There are three classes of antecedent soil moisture conditions: Class I occurs when little rainfall has occurred during the five preceding days; Class II occurs when moderate rainfall has occurred; and Class III occurs when substantial rainfall has occurred (see Table 8) (Dunne and Leopold, 1978). The curve number for a drainage area is adjusted upward if there is over 1.1 inches of rain during these five days (e.g., more stormwater runoff may occur) and downward if less than 0.5 inch of rain occurs during this time period (e.g., less stormwater runoff may occur).

Table 8: Rainfall Limits for Estimating Antecedent Soil Moisture

Antecedent Soil Moisture Class	5-Day Total Antecedent Rainfall (inches)
I	< 0.5
II	0.5 – 1.1
III	> 1.1

Source: Dunne and Leopold, 1978.

When necessary, we adjusted the curve numbers for each of the three land uses based on the precipitation that fell during the five preceding days (see Table 9).

Table 9: Adjustment of Curve Numbers for Antecedent Soil Moisture, Class II, to Curve Numbers for Class I (Drier) and Class III (Wetter)

Type of Land Use	Curve Number for Antecedent Soil Moisture, Class II	Curve Number for Antecedent Soil Moisture, Class I	Curve Number for Antecedent Soil Moisture, Class III
Residential	80	63	91
Commercial	92	80	97
Urban	90	78	96

Source: Dunne and Leopold, 1978.

VOLUME OF STORMWATER RUNOFF CAPTURED

Although infiltration basins have a certain volume capacity, the actual volume of water that they capture depends not only on this size but also on the magnitude and frequency of the precipitation event and the infiltration rate of the soil. Large storms result in large volumes of stormwater runoff that may exceed the capacity of the infiltration basin. When the volume of runoff exceeds the capacity of the infiltration basin, we assumed that the excess was lost and only the volume capacity of the infiltration basin was captured.

Additionally, large storms commonly occur over several days. When a large volume of runoff is captured during a day, the maximum volume that may be captured the next day is restricted by the volume that remains in the basin from the previous day. The volume remaining from the previous day was determined by multiplying the depth captured the previous day (based on volume) by the rate at which that depth will infiltrate the soil, thereby draining the basin and allowing further volumes to be captured. For example, an infiltration basin with a surface area of 0.1 acre and a depth of two feet has a volume capacity of 0.18 AF. When a storm generates a volume of runoff that exceeds this capacity within a 24-hour period, the excess volume of runoff will be lost. Assuming an infiltration rate of 0.5 inch per hour (1 foot per day), the maximum volume that may be captured the following day is 0.09 AF, since only half of the 1.8 AF captured the previous day will have infiltrated.

Using ten years of precipitation data, from 1991-2000, we calculated the average volume of stormwater runoff that could be captured each year from a five-acre drainage area by basins of four different sizes. For each of the four basin sizes, we calculated volume capture under three infiltration rates common for the soils in this area: 0.5 inch per hour, 1 inch per hour, and 2 inches per hour (USDASCS, 1980). The curve number of each land use was adjusted according to the time interval between precipitation events and the magnitude of these events to account for the effects of antecedent soil moisture on the generation of stormwater runoff, as previously discussed.

In order to provide the maximum volume that could be captured, we did not account for any evapotranspiration that may occur. We assumed that the volumes of water captured by the basin and the volumes of water infiltrated by the basin occurred at the end of a 24-hour interval (i.e., the calculations do not account for a volume of runoff that will be infiltrating as the basin continues to capture additional runoff). We then weighted the resulting average volume captured per year by the land use of the drainage areas, according to the land use distribution in the ULARA. We assumed that each 5-acre drainage area contained 69% residential, 18% urban and 13% commercial land uses, as this is the characteristic distribution of the urban or built-up land use category in the ULARA (EPA, 1999a). Total volumes captured per year by each basin are presented in Table 10. Appendix C contains graphs depicting the volume of runoff captured by each basin from each homogeneous land use (purely residential, commercial, or urban) over the ten-year period, as well as the average volume weighted by land use distribution.

Table 10: Volume of Runoff Captured Per Year

Basin Size (acres)	0.1		0.5	
Infiltration Rate (in/hr)	Basin Depth (ft)		Basin Depth (ft)	
	2	3	2	3
0.5	0.90	1.10	1.71	1.87
1.0	0.96	1.15	1.73	1.87
2.0	0.96	1.18	1.87	1.87

The results indicate that smaller basins capture stormwater runoff more efficiently than larger basins. Holding surface area constant, an increase in depth from two feet to three feet does not lead to a correspondingly large increase in volume captured. A five-fold increase in basin surface area (from 0.1 acre to 0.5 acre) results in less than double the runoff capture, and capture efficiency decreases with increasing infiltration rate. This suggests that smaller basins, even on soils with lower infiltration rates, are more efficient at capturing runoff than larger basins. These results are significant in the overall evaluation of this strategy, since the smaller the basin, the easier it is to place in an urban area.

CONCLUSION

We calculated the average volume of stormwater runoff that could be captured from a five-acre drainage area each year by infiltration basins of four sizes under a range of infiltration rates. A 0.1-acre infiltration basin with a depth of two feet can capture from 0.90 AF per year to 0.96 AF per year, depending on the infiltration rate, while an infiltration basin with the same surface area and a depth of three feet can capture from 1.10 AF per year to 1.18 AF per year. A 0.5-acre infiltration basin with a depth of two feet can capture from 1.71 AF per year to 1.87 AF per year. A 0.5-acre infiltration basin with a depth of three feet will capture 1.87 AF per year under the three infiltration rates that we studied.

The stormwater runoff captured by these basins contains contaminants that may adversely affect groundwater and, consequently, drinking water supplies. Therefore, the next step in our analysis was to determine if stormwater runoff, once infiltrated, would contaminate groundwater supplies. In the next section, we present our calculation of the depth to groundwater necessary to prevent contamination from occurring.

REMOVAL OF STORMWATER CONTAMINANTS

INTRODUCTION

Since the ultimate goal of a groundwater recharge project is to resupply an aquifer with water that does not impair the quality of existing groundwater, the role of the unsaturated zone, or vadose zone, is to remove or transform harmful contaminants in the water as it moves through the soil toward groundwater. The unsaturated soil layer has the ability to remove contaminants from infiltrated stormwater, reducing potential health risks before it reaches the aquifer (NRC, 1994).

The unsaturated zone is a much more complex transport medium than the saturated zone. Soil pores are only partially filled with water, so chemicals with a high vapor pressure are able to move in the gas phase as well as in solution. In addition, the water flow rate can vary significantly, as the resistance by soil to the flow of water through a given soil volume is a non-linear function of the water content, while in the saturated zone it is a constant.

A relatively simple approach of modeling contaminant transport in the unsaturated zone is a one-dimensional equation that includes adsorption and degradation processes. This equation has been modified for use in the unsaturated zone. Using concentrations of stormwater contaminants from data gathered by the LACDPW and the EPA, we established the proportion that would be removed by different soil types in the San Fernando Valley. From this, we determined the depth to groundwater necessary to prevent aquifer contamination.

CONTAMINANT REMOVAL PROCESSES

Contaminant removal processes that occur in soil depend on characteristics of both the contaminants and the soil. The quality of infiltrated stormwater can change in the subsurface environment as a result of one or more of the following processes: filtration, adsorption, degradation, volatilization, precipitation, and complexation.

FILTRATION

Particulate contaminants include microorganisms (large pathogens such as parasites and some bacteria) and other undissolved materials. Particulates that infiltrate the subsurface are retained by filtration as they move through small pores. Filtration slowly clogs the medium and reduces its permeability if contaminants are not degraded (O’Hare et al, 1986, and NRC, 1984).

ADSORPTION

Dissolved contaminants may be adsorbed by soil particles, impeding their movement. Adsorption involves the preferential partitioning of substances in the liquid phase onto the surface of a solid substrate. The substance is separated from the liquid and accumulates at the surface of a solid such as soil. The adsorbing solid is the adsorbent, and the material concentrated or adsorbed at the surface of that solid is the adsorbate. Physical adsorption is caused mainly by van der Waals forces and electrostatic forces between adsorbate molecules and the ions of the adsorbent surface. Therefore, adsorbents are characterized by surface properties such as surface area and polarity. A large specific surface area is preferable for providing large adsorption capacity. Surface polarity corresponds to affinity with polar substances such as water. Polar adsorbents are hydrophilic, as they are attracted to water and tend to remain in solution rather than adsorb. Conversely, non-polar adsorbents are generally hydrophobic and tend to come out of solution to sorb to soil surfaces (O'Hare et al., 1986).

DEGRADATION

Contaminants may be degraded by abiotic (chemical or physical) or biotic processes. Degradation involves the breaking of chemical bonds and the subsequent formation of new ones, offering the potential of permanent conversion into harmless products (Watts, 1998). Abiotic reactions include hydrolysis, oxidation-reduction, and photolysis. Hydrolysis is the addition of water to a molecule and is often enhanced by the presence of acids or bases. During oxidation-reduction (redox) reactions, a contaminant is either oxidized (the addition of oxygen or loss of electrons or a hydrogen atom) or reduced (the addition of a hydrogen atom or electrons). Redox reactions involve the transfer of electrons from one atom to another; electrons are neither created nor destroyed. Therefore, oxidation and reduction are linked, and it is impossible to have one without the other. The redox potential of the system depends on pH, dissolved oxygen concentration, and the presence of oxidizing or reducing agents such as ultraviolet light, ozone, and oxygen radicals. Photolysis is a light-induced redox reaction that has limited importance in the transformation of chemicals in the vadose zone because they are not exposed to light (Watts, 1998).

In biotic degradation, microorganisms metabolize contaminants through biochemical redox reactions. Microorganisms often use organic contaminants as a carbon source to make cellular material and as a source of energy for growth, reproduction, and motility. Of the common degradation mechanisms (hydrolysis, oxidation-reduction, photolysis, and biodegradation), biodegradation is the most significant process for the decomposition of organic contaminants in the natural environment (Bitton and Gerba, 1984). This process is likely to occur when microorganisms attach to surfaces and is enhanced if the soil is fine and has a high specific surface area, such as in sand or silt. However, fine soil may be clogged by bacterial growth. In coarse soil, biodegradation is less rapid and less extensive than in fine soil, but there is less chance of clogging (O'Hare et al., 1986)

VOLATILIZATION, PRECIPITATION, AND COMPLEXATION

Some chemicals volatilize, or move from the liquid phase to the gas phase within the soil, and then move upward and into the atmosphere. Volatile chemicals have a Henry's Law constant greater than 10^{-5} atmospheres per cubic meter per mole and a molecular weight of less than 200 grams per mole (EPA, 2000b). Other contaminants may precipitate out of solution if their concentration exceeds their solubility, meaning that the solid separates from the liquid. Contaminants may also attach to soil mineral or organic surfaces, forming complexes with these other particles. Metals often precipitate or form complexes; these processes will be discussed further below.

CONCENTRATIONS OF STORMWATER CONTAMINANTS

In order to determine the effect on groundwater quality from infiltration of contaminated stormwater, we analyzed the concentrations of stormwater contaminants contained in two data sets: 1998-99 Seasonal Event Mean Concentrations (EMCs) collected in Los Angeles County by the LACDPW and NURP data collected from areas across the nation by the EPA between 1978 and 1983. There are some overlaps in the LACDPW's data and the EPA's data; for example, each provides data for nutrients and metals. In this case, we chose to use the LACPDW data since it is specific to Los Angeles County. However, there are many contaminants that the LACPDW did not test for or did not detect above the detection limit in an appropriate number of cases. Therefore, we supplemented the LACPDW's data with NURP data, as the EPA tested for and detected more contaminants than the LACDPW.

The LACDPW monitored and assessed contaminants in stormwater runoff from eight land uses: high-density residential, light industrial, vacant, retail/commercial, multi-family residential, transportation, education, and mixed residential. These eight land uses were identified as the most significant land use categories in Los Angeles County and represent over 86% of all land use. Stormwater contaminants attributed to each land use category come from a drainage area comprised predominantly of this single land use (LACDPW, 1999). We considered data from three land uses – retail/commercial, education, and mixed residential – that were considered representative of land uses among which an infiltration basin would be placed. Retail/commercial land use is comprised of commercial office buildings, small shops, restaurants, hotels, and high-density apartments. Education land use is characterized by a university campus, and mixed residential land use includes apartments and single-family houses. These land uses were assumed to be comparable to the residential, urban, and commercial land uses for which we calculated volume of runoff that will be infiltrated.

Contaminants detected by the LACDPW in statistically meaningful concentrations included nutrients and metals: dissolved phosphorus, total Kjeldahl nitrogen, ammonia-nitrogen, nitrate-nitrogen, nitrite-nitrogen, suspended solids, total phosphorus, total and dissolved copper, total lead, total and dissolved nickel, and total and dissolved zinc. The LACDPW did not test for cyanide, oil and grease, total petroleum hydrocarbons, total phenols, and bacteria (fecal coliform, fecal enterococcus, fecal streptococcus, and total coliform). The LACDPW did not gather enough data above the detection limit to provide event mean concentrations of pesticides and organic chemicals (except Diazinon, which we did not consider since there is very little information available on its reaction in the environment). The full data set is shown in Appendix D.

Based on the availability of significant data, we considered seven contaminants detected by the LACDPW: nitrate-nitrogen, nitrite-nitrogen, dissolved phosphorus, dissolved copper, dissolved lead, dissolved nickel, and dissolved zinc. We did not consider suspended solids, oil and grease, or undissolved forms of phosphorus, copper, lead, nickel, or zinc, as these contaminants are likely to be deposited or filtered out at the surface and would not infiltrate the soil. We examined both the EMCs and seasonal maximum concentrations of these contaminants. Although it is commonly believed that the highest contaminant concentrations are found in stormwater from the first storm of the season, since contaminants have been building up since the last storm of the previous season, this was not necessarily the case.

We compared both mean and maximum stormwater concentrations with drinking water standards, known as Maximum Contaminant Levels (MCLs), set by the EPA and the California Department of Health Services (DHS). MCLs were established as part of the Safe Drinking Water Act (SDWA) to protect public health and are derived from Maximum Contaminant Level Goals (MCLGs), which are non-enforceable goals based on extremely low risk. The EPA has been given the directive to set MCLs as close to MCLGs as possible, but this is often infeasible due to the limits of water treatment technologies and analytical detection limits (Watts, 1998). There are both primary and secondary MCLs; primary MCLs are legally enforceable standards regulating contaminants that can adversely affect public health, while secondary MCLs are non-enforceable guidelines regulating contaminants that may cause cosmetic or aesthetic effects in drinking water (EPA, 2000a). All contaminants obtained from the LACDPW data have primary MCLs, except for zinc, which has only a secondary MCL. We set acceptable concentrations of stormwater contaminants after infiltration as each contaminant’s primary MCL or, if no primary MCL had been set, secondary MCL.

MCLs are used in hazardous waste management as Applicable or Relevant and Appropriate Requirements (ARARs) for groundwater cleanup criteria at Superfund sites. They are also used by many state and local regulatory agencies as de facto remediation standards for contaminated groundwater (Watts, 1998). Since they are often used as cleanup criteria, and since the infiltrated groundwater will be used as drinking water, MCLs are appropriate as a standard for comparison to mean and maximum concentrations of stormwater contaminants. These comparisons are shown in Table 11. Neither the EMCs nor the seasonal maximum concentrations of nutrients and metals found in stormwater by the LACDPW exceed MCLs.

Table 11: Comparison of LACDPW's Stormwater Contaminant EMCs and Seasonal Maximum Concentrations to MCLs

Contaminant	Units	Concentration from Different Land Uses Mean (Maximum)			
		Retail / Commercial	Education	Mixed Residential	MCL
Nitrate-Nitrogen	mg/L	0.59 (0.95)	0.91 (1.55)	0.90 (1.34)	10
Nitrite-Nitrogen	mg/L	0.17 (0.289)	0.06 (0.088)	0.10 (0.514)	1
Dissolved Phosphorus	mg/L	0.40 (0.89)	0.34 (0.218)	0.19 (0.357)	---
Dissolved Copper	µg/L	14.86 (42.5)	20.48 (39.8)	12.82 (22.8)	1300
Dissolved Lead	µg/L	n/m (8)	n/m (0)	n/m (0)	15
Dissolved Nickel	µg/L	n/m (7.2)	n/m (7.2)	n/m (0)	100
Dissolved Zinc	µg/L	182.58 (290)	95.87 (114)	114.94 (157)	5000*

n/m: not meaningful, not enough data above detection limit.
** Secondary MCL.*
Source: Derived from LACDPW, 1999; DHS, 2000; DHS, 2001; and EPA, 2000a.

Since the LACDPW tested for or detected in meaningful concentrations only nutrients and metals (and Diazinon, which we are not considering), we supplemented this Los Angeles-specific data with data for toxic contaminants collected by the EPA. During the National Urban Runoff Program, 121 stormwater samples from 17 cities in the United States were analyzed, and toxic compounds found in greater than 10% of stormwater outfalls were reported. Since the EPA did not find any regional differences in the toxic contaminants detected or in their concentrations (NRC, 1994), this data can be applied to Los Angeles, even though it is not specific to the region. The NURP data provides a range of concentrations of twelve toxic stormwater contaminants found in a significant number of outfalls. To be conservative, we analyzed the removal of the highest concentration of each contaminant.

If an MCL had been set for a contaminant, we compared it to the highest detected concentration of each contaminant. If no MCL existed, we compared the highest detected concentration of a contaminant to its Preliminary Remediation Goal

(PRG) for Tap Water used by the EPA for planning purposes. PRG concentrations can be used as an initial cleanup goal for contaminated sites, as they provide an estimate of contaminant concentrations that protect human health. Concentrations above these levels do not automatically designate a site as contaminated; however, exceedance of a PRG suggests further evaluation of the potential risks that may be posed by these contaminants (EPA, 2000b). Table 12 shows a comparison of the highest reported concentration of each contaminant to its corresponding MCL or PRG.

Table 12: Comparison of the EPA's Toxic Stormwater Contaminant Concentrations to MCLs and PRGs

Contaminant	Concentration (mg/L)	MCL or PRG
Chlordane	0.01	0.002
Chrysene	0.010	0.0092*
α-Endosulfan	0.0002	0.22*
bis(2-Ethylhexyl) Phthalate	0.062	0.006
Fluoranthene	0.021	1.5*
Lindane	0.0001	0.0002
Methylene Chloride	0.015	0.005
4-Nitrophenol	0.037	---
Pentachlorophenol	0.115	0.001
Phenanthrene	0.010	---
Phenol	0.013	22*
Pyrene	0.016	0.18*

** PRG.*

Source: Derived from NRC, 1994; EPA, 2000a; and EPA, 2000b.

Neither phenanthrene nor 4-nitrophenol has an MCL or PRG. Since we had no standard to which to compare them, we did not analyze them. Of the ten other toxic contaminants detected by the EPA, five were found in a concentration exceeding their corresponding MCL or PRG: chlordane, chrysene, bis(2-ethylhexyl) phthalate, methylene chloride, and pentachlorophenol. Therefore, we analyzed the proportion of these five contaminants removed by the soil at different depths.

REMOVAL OF NUTRIENTS, METALS, AND PATHOGENS

The concentrations of contaminants obtained from LACDPW data did not exceed MCLs; thus, no further quantitative analysis of their removal in the soil was necessary, as they will not be present in groundwater in concentrations above the MCLs. However, it is important to understand the processes affecting these contaminants as they move through the subsurface. Nutrients and metals are both affected by several processes within the vadose zone, as are pathogens. Although Los Angeles County did not test for pathogens, they are a common component of stormwater, so they have also been considered.

NUTRIENTS

Both nitrogen and phosphorus are cyclic elements that exist in compounds that may be decomposed or synthesized, resulting in a change from the original form (Pitt et al., 1996). If the surface of an infiltration basin is vegetated, the vegetation may take up nutrients from stormwater that infiltrates the root zone. Nutrient leachates usually move vertically through the soil and dilute rapidly downgradient from their source. During percolation through the soil, some nutrients are removed, significantly reducing the nutrient concentrations reaching groundwater. Phosphorus, in the form of soluble orthophosphate, may either precipitate from solution or adsorb onto soil surfaces through phosphorus fixation. This is a two-step reaction during which phosphorus sorbs onto exposed iron, aluminum, or calcium on solid soil surfaces and then converts into mineraloids or minerals (Pitt et al., 1996).

When nitrogen-containing compounds come into contact with soil, the potential exists for nitrate to leach into groundwater, as it is highly soluble and will stay in solution as it infiltrates toward groundwater. Under anaerobic conditions, nitrogen can be removed from the soil by denitrification, the transformation by bacteria of nitrate (NO_3^-) into nitrogen gas (N_2). Denitrifying bacteria consume organic matter while utilizing NO_3^- as their electron acceptor. The process can occur only in the presence of organic matter and these denitrifying bacteria.

METALS

Two main soil parameters that affect the mobility of metals are oxidation-reduction conditions and pH. In general, reduced forms of metals are more mobile than their oxidized counterparts, as most oxidized metals are significantly less soluble than those in lower oxidation states. Acidic environments promote metal mobility, as an increase in pH of the system decreases the solubility of metals and causes them to come out of solution. Undissolved particulate metals that are not dissolved are filtered out at the soil surface. Most metals are not very soluble at typical stormwater pH values and, therefore, are readily filtered by the soil (Pitt et al., 1996).

Dissolved metals will not be filtered at the surface, but may be removed through one of several processes: adsorption, ion exchange, precipitation, solid-state diffusion into soil minerals, complexation, and chelation. Dissolved metal ions are reduced from stormwater mostly by adsorption onto soil in the vadose zone. Partitioning of metals on soil surfaces decreases the aqueous concentration, and, correspondingly, metals' ability to move in the subsurface. Adsorption of metals to soils can occur through physical sorption due to the attraction of long-range Van der Waals forces. Metals have different affinities for solids; that is, they prefer to sorb to some solids much more than they prefer to sorb to others. In addition, sorbents have different affinities for metals; that is, they prefer to sorb to some metals much more than they prefer to sorb others. Competition between solids or between metals will affect the overall adsorption ability of various trace metals (Pitt et al., 1996).

Ion exchange is a kind of chemical sorption during which one ion displaces another that was originally present on the exchange surface. Most heavy metals have a positive charge in soil and a subsequent affinity to the negative charge of the soil. Clay surfaces have negative charges that must be balanced by cations in order to maintain the soil's neutral charge. However, cations that are present at any given time may be displaced by other cations that have a higher affinity for the soil surface. Although one metal may displace another on the exchange sites, these sites are always filled to maintain electroneutrality (Watts, 1998).

Another significant mechanism for the removal of metals from water is precipitation, in which the solubility of the metal is exceeded, causing it to come out of solution. This generally occurs at increased pH due to the corresponding decrease in solubility. A process similar to precipitation is co-precipitation, where a metal is enmeshed or sorbed to another species that is undergoing precipitation (Watts, 1998).

Metals may also undergo chelation in the soil. During this process, a bond is formed between a metal ion and an organic molecule. The resulting complex of metal bound to molecule, or chelate, binds the metal ion so firmly that it cannot escape. Metals may also form ligands or complexes with organic or inorganic anions. The ligand often carries a positive or negative charge and may not be highly hydrophobic. A range of sorption effects may be seen with complexes; the complex may have either a higher sorption affinity or a higher solubility than the free metal. Therefore, complexation complicates the partitioning of metals in soils and makes quantification difficult. In addition, organic molecules may be decomposed, freeing the metals and allowing them to react with other compounds that then become immobilized in the soil profile. These immobilization reactions are more pronounced at high pH and in an aerobic environment. Organic complexation of a metal may enhance the metal's ability to move freely through the soil, as organic complexes are either uncharged or negatively charged. Therefore, they are not attracted to negatively charged adsorption or ion exchange sites and are not easily removed from solution (Pitt et al., 1996).

PATHOGENS

Pathogenic microorganisms such as bacteria and viruses will move through soil in the liquid phase until they are filtered, adsorbed onto soil particles, or inactivated. Bacteria may be filtered out in the top layer of soil, while viruses tend to be transported farther into the soil because of their much smaller size. Soil characteristics affect the mobility of microorganisms in soil; fine-textured soils filter microorganisms more effectively than coarser-textured soils. Soils with higher organic content also retain microorganisms more effectively. If microorganisms are not filtered at the surface, they may be adsorbed or inactivated within the vadose zone.

Microbial adsorption is promoted by increased cation concentration, decreased pH, and low soluble organic content (Pitt et al., 1996). Cations increase adsorption because they reduce repulsive forces on both pathogens and surfaces of soil particles; however, large volumes of water reduce sorption because water has low conductivity. When water flow rate increases, fewer pathogens adsorb to soils. Low pH increases adsorption, as pathogens become more electropositive than the soil in acidic conditions (NRC, 1994). The presence of soluble organic chemicals reduces virus adsorption because these chemicals compete with viruses for adsorption sites.

Factors that affect the survival rates of bacteria and viruses in soil include pH, temperature, moisture content, dissolved oxygen levels, and organic content. Depending on a microorganism's specific adaptation mechanisms, changes in any one of these parameters may be detrimental to the microorganism, resulting in its inactivation. In general, environments of high acidity and high temperature reduce the survival time of pathogens. Higher dissolved oxygen levels lead to virus inactivation, as oxidation of its capsid destroys the virus. Drier soil conditions also promote inactivation (NRC, 1994); thus, pathogens may be inactivated deliberately by allowing the infiltration basin to dry out intermittently. As it dries, pathogens multiply until their food sources and oxygen are depleted. Once this occurs, they die and further growth is inhibited (O'Hare et al, 1986).

Survival rates of microorganisms can be calculated using a general exponential decay function. For specific sites, a stepwise regression can be performed in order to determine which physical and chemical characteristics of certain soils have the most significant effect on the survival rates of bacteria and viruses (Hurst, 1997).

REMOVAL OF ORGANIC CONTAMINANTS

Five contaminants detected by the EPA were present in stormwater in concentrations above their MCLs or PRGs. We calculated the concentrations of these contaminants as the infiltrated stormwater moves through the vadose zone, using an equation that accounts for adsorption, degradation, and dispersion. The equation does not consider volatilization, which is unnecessary since none of the five contaminants are volatile. It also does not consider remobilization of contaminants once they have been adsorbed, as they will not desorb. The following equation results in the ratio of contaminant at a certain time and distance away from the source to its initial concentration (Watts, 1998):

$$\frac{C(y,t)}{C_0} = \frac{1}{2}[\exp(A_1)\cdot \mathrm{erfc}(A_2)]\text{, where}$$

C_0 = initial contaminant concentration in water (mg/L)

$C(y,t)$ = contaminant concentration in water (mg/L) at a certain time and depth

$$A_1 = \frac{y}{2D'_y}\left(v'_y - \sqrt{v'^{\,2}_y + 4D'_y k'}\right)$$

$$A_2 = \frac{y - t\sqrt{v'^{\,2}_y + 4D'_y k'}}{2\sqrt{D'_y t}}$$

$$D'_y = \frac{D_y}{R}$$

$$v'_y = \frac{v_y}{R}$$

$$k' = \frac{k}{R}$$

v_y = pore-water velocity (m/d)

D_y = groundwater dispersion coefficient (m^2)

k = first-order rate constant for contaminant degradation (d^{-1})

R = retardation factor (-)

t = time (d)

y = depth (m).

This equation was designed for use in the saturated zone; however, it can be applied to the unsaturated zone by using water content in place of porosity (Watts, 1998). A primary difference between the saturated zone and the vadose zone is the amount of water present in the pores. When this equation is applied to saturated soil, the value of porosity is used because, under saturated conditions, the pore space is equal to the volume of water within the soil. In unsaturated soil, however, the soil moisture content is used because water can travel through only pore spaces that are already wet. If the pore spaces are dry, water will remain to fill them rather than moving through them. Since we studied contaminant transport in the vadose zone, we modified the equation throughout by using soil moisture content in place of porosity.

This equation assumes that the inflow of contaminants through the infiltration basin is continuous throughout the storm season, instead of occurring only during and shortly after discrete precipitation events throughout the season. Although an infiltration basin would repeatedly fill and drain throughout the storm season, this equation does not take that into account and instead assumes that water would be infiltrating continually during each time period modeled. However, given the typical rainfall characteristics in the Los Angeles region, the basin would likely remain dry for extended periods of time.

We examined the removal of the five selected contaminants in the three types of soil that prevail in the San Fernando Valley region: silty clay loam, sandy loam, and clay loam (USDASCS, 1980). These soils differ in their bulk density (see Table 13) and other characteristics that affect their capability for removal of contaminants, as discussed below.

Table 13: Soil Bulk Densities of Three Soil Types

Soil Bulk Density (g/cm³)		
Silty Clay Loam	**Sandy Loam**	**Clay Loam**
1.27	1.53	1.31

Source: Juma, 1999.

PORE-WATER VELOCITY

Contaminants move through the subsurface by two primary modes: advection and dispersion. Advection refers to the physical movement of fluids in response to gravitational gradients and can be described by pore-water velocity, which is the advective flux or the bulk movement (often considered the average movement) of the water. The pore-water velocity of the infiltrated stormwater must take into account the cross-sectional area of the soil through which it is flowing:

$v = \frac{-K}{\Theta}$, where

K = unsaturated hydraulic conductivity (m/s), a non-linear function of θ

θ = soil moisture content (cm^3/cm^3).

Hydraulic conductivity measures the ease with which a fluid passes through a porous media when submitted to a gradient. The greater the hydraulic conductivity, the more readily the fluid passes through the medium. Hydraulic conductivity depends on soil texture and the amount of fluid present in the soil.

Saturated flow occurs when the soil's total pore space is filled with water. Values of saturated hydraulic conductivity have been defined for different soil types and vary by several orders of magnitude, depending on soil type and degree of consolidation. A distinction must be made between hydraulic conductivity under saturated conditions and hydraulic conductivity under unsaturated conditions, as the latter parameter increases non-linearly with increasing soil moisture content until the soil reaches saturation. Therefore, saturated hydraulic conductivity cannot be used to describe water movement under unsaturated conditions.

In order for us to determine the ease with which stormwater will infiltrate the soil under a variety of soil moisture conditions, we calculated the unsaturated hydraulic conductivity for each selected soil type at several different soil moisture contents. Unsaturated hydraulic conductivity may be either measured directly through experimentation or estimated indirectly through prediction from more easily measured data. We used a mathematical model developed by the United States Department of Agriculture (USDA) to estimate unsaturated hydraulic conductivity from empirically determined surrogate soil data such as soil texture data and bulk density (Schaap, 1999).

The model allows prediction of unsaturated hydraulic conductivities from fitted retention parameters developed by van Genuchten (1980) (qtd. in Schaap, 1999): θ_r, θ_s, α, n, and L. Each soil type has a residual water content (θ_r), also called specific retention, which is a measure of the water-retaining capacity of the soil and is expressed quantitatively as a ratio of the total volume of pore space occupied by water that will be retained in these pores against the force of gravity to the total volume of the soil. Saturated water content (θ_s), also referred to as the total porosity, is defined as a ratio of the maximum volume of water occupying pore space to the total volume of the soil. Saturated water content is equivalent to total porosity, which is defined as a ratio of the maximum volume of pore space to the total volume of the soil. The parameters α and n are used to fit the equation, and L is an empirical parameter that represents tortuosity, or the convoluted path that the water must take as it moves through soil pores (Schaap, 1999).

For each soil type, the model uses average values of hydraulic parameters, as shown in Table 14. Values for θ_r, θ_s, α, and n were generated by computing the average values for each soil type based on the number of samples of each (140, 476, and 172 for clay loam, sandy loam, and silty clay loam, respectively). The USDA generated values for K_0 and L by inserting each soil type's average values of θ_r, θ_s, α, and n into another model.

Table 14: Class Average Values of Hydraulic Parameters

Soil Type	q_r **(cm^3/cm^3)**	q_s **(cm^3/cm^3)**	a **(1/cm)**	**n ---**	**L ---**
Clay Loam	0.079	0.442	0.0158	1.42	-0.763
Sandy Loam	0.039	0.387	0.0267	1.45	-0.861
Silty Clay Loam	0.090	0.482	0.00839	1.52	-0.156

Source: Derived from Schaap, 1999.

In order to calculate unsaturated hydraulic conductivity, we began by determining the relative saturation of the soil, using van Genuchten's water retention function rewritten to yield the relative saturation. Relative saturation, S_e, is defined as the percentage of soil saturation and depends on residual and saturated water contents. Although two different soils may contain the same absolute volume of water, their relative saturation will be different as their residual and saturated water contents are different. The following equation was used to find relative saturation:

$$S_e = \frac{q - q_r}{q_s - q_r}, \text{ where}$$

θ = actual moisture content of the soil.

Once the relative saturation was found, it was used to establish the hydraulic conductivity of the soil at that level of saturation. The USDA model combines the previous van Genuchten equation with Mualem's (1976) (qtd. in Schaap) pore-size distribution model to yield the van Genuchten-Mualem model (van Genuchten, 1980, qtd. in Schaap, 1999):

$$K(S_e) = Ko(Se)^L\{1-[1-S_e^{n/(n-1)}]^{1-1/n}\}^2$$

Soil may hold a volume of water ranging between residual water content and saturated water content. We found hydraulic conductivities for the three prominent San Fernando Valley soils at varying soil moisture contents. If a soil contains only its residual water content, there will be no movement of water through the pores. Therefore, we calculated unsaturated hydraulic conductivities for each soil at a value slightly above (0.01) residual water content. We then calculated hydraulic conductivities at a soil moisture content of 0.1, increasing in intervals of 0.1 until saturation point, at which point we calculated a hydraulic conductivity similar to saturated hydraulic conductivity. These hydraulic conductivities are shown in Table 15 as a function of soil moisture content; graphs of these hydraulic conductivities are shown in Appendix E.

Table 15 : Unsaturated Hydraulic Conductivities of Three Soil Types as a Function of Soil Moisture Content

Soil Moisture Content (cm^3/cm^3)	Unsaturated Hydraulic Conductivity (cm/d)		
	Clay Loam	**Sandy Loam**	**Silty Clay Loam**
0.04	--	9.62E-15	--
0.08	1.92E-16	--	--
0.091	--	--	4.58E-16
0.1	1.64E-08	8.97E-05	2.24E-10
0.2	6.11E-04	2.14E-02	1.92E-04
0.3	2.57E-02	4.16E-01	8.38E-03
0.387	--	1.55E+01	--
0.4	4.10E-01	--	1.05E-01
0.442	5.00E+00	--	--
0.482	--	--	2.23E+00

DISPERSION

Dispersion is the other means by which a contaminant moves in the subsurface. When a dissolved contaminant disperses, it spreads down a concentration gradient, resulting in decreased concentration (Watts, 1998). Spreading occurs due to the water's interaction with soil particles and the difference in tortuosity, or crookedness of the path the water takes as it infiltrates the soil. Dispersion is a linear function of water velocity and distance traveled by the contaminant. The dispersivity coefficient (D_y) is usually estimated by multiplying the distance traveled by the pore-water velocity and by a factor of ten (Gelhar et al., 1992).

RETARDATION FACTOR

A contaminant that moves with water but has the ability to adsorb to soil will move with a different velocity than that of water. This effect is known as retardation and is represented by the retardation factor, which provides an estimate of the velocity of water in the subsurface relative to the velocity of the contaminant. The retardation factor is quantitatively described by the following equation:

$$R = 1 + \frac{r_B \cdot K_d}{\Theta}, \text{ where}$$

ρ_B = soil bulk density (g/cm^3)

K_d = soil distribution coefficient (mL/g)

θ = soil moisture content (cm^3/cm^3).

The soil distribution coefficient, K_d, represents the degree to which a contaminant will partition between the sorbed and bulk soil-water phases. It is the ratio of mass of contaminant sorbed to soil (mg/g) to mass of contaminant dissolved in water (mg/mL). The most accurate representation of K_d is determined experimentally, as numerous site-specific soil characteristics affect soil sorptivity. Of these, soil organic carbon content has the highest correlation, since hydrophobic contaminants sorb strongly to the non-polar core material of soil organic matter (Watts, 1998). Because organic matter is the most common sorbent, K_d can be estimated mathematically using the following equation, which incorporates the amount of organic matter in soil:

$K_d = K_{oc} \cdot f_{oc}$, where

K_{oc} = soil adsorption coefficient (mL/g)

f_{oc} = fraction of organic content in soil.

The soil adsorption coefficient, K_{oc}, represents the degree to which a contaminant will partition between the organic carbon-sorbed and bulk soil-water phases. It is the ratio of mass of contaminant sorbed to the soil organic carbon (mg/g) to mass of contaminant dissolved in water (mg/mL). K_d is obtained by normalizing K_{oc} by the fraction of organic content in the soil. Although organic fraction varies from soil to soil, we assumed this percentage to be 2% for all soils, as this is a typical value (Watts, 1998).

General soil adsorption coefficients have not been determined for many chemicals, so it was necessary for us to calculate these coefficients. We used regression equations based on the hydrophobicity of each chemical as represented by the octanol-water partition coefficient, K_{ow}. Determined experimentally, K_{ow} is the ratio of the concentration of contaminant in water-saturated *n*-octanol (mg/L) to the concentration in *n*-octanol-saturated water (mg/L). Regression equations, shown in Table 16, were developed for compound classes to relate K_{oc} to K_{ow}. Once K_{oc} was

Table 16: Regression Equations for Determining Soil Adsorption Coefficients

Contaminant	**Regression Equation**	**Log K_{ow}**	**Log K_{oc}**	**K_d**
Chlordane	$\log K_{oc} = 0.52 \log K_{ow} + 0.64$	6	3.76	11.5
Chrysene	$\log K_{oc} = \log K_{ow} - 0.21$	5.71	5.50	633
bis(2-Ethylhexyl) Phthalate	$\log K_{oc} = 0.544 \log K_{ow} + 1.377$	4.66	3.91	16.3
Methylene Chloride	$\log K_{oc} = 0.544 \log K_{ow} + 1.377$	1.28	2.07	0.237
Pentachlorophenol	$\log K_{oc} = 0.544 \log K_{ow} + 1.377$	4.41	3.78	11.9

Source: Derived from Watts, 1998.

determined from K_{ow}, we could calculate K_d and therefore the retardation factor. Pore-water velocity, dispersion, and the first-order rate constant were all divided by the retardation factor to normalize for the effects of adsorption.

FIRST-ORDER RATE CONSTANT FOR CONTAMINANT DEGRADATION

A half-life is the time required for 50% of a contaminant to degrade. Contaminants will degrade at different rates under different degradation processes; therefore, half-lives vary depending upon which degradation process is being considered. In general, though, a contaminant is degraded by one dominant process.

For each contaminant, we used the half-life for this most important degradation pathway, which was usually biodegradation. To be conservative, we selected the lowest degradation rate of the range given for the most important pathway (Howard, 1991). The first-order rate constant, shown in Table 17, was determined from these half-lives through a modification of the first-order rate equation:

$C_t = C_0 e^{-kt}$, where

C_0 = initial concentration (mg/L)

C_t = concentration at time t (mg/L)

k = first-order rate constant (1/d)

t = time (d).

Table 17: Half-Lives of Selected Contaminants

Contaminant	Half-Life (d)	Degradation Rate (1/d)
Chlordane	1386	5.00E-4
Chrysene	1000	6.93E-4
bis(2-Ethylhexyl) Phthalate	23	3.02E-2
Methylene Chloride	28	2.48E-2
Pentachlorophenol	178	3.89E-3

Source: Derived from Howard, 1991.

DISTANCE AND TIME

We varied distance and time to provide an overview of resulting contaminant concentrations under different conditions. For each contaminant and each soil type (with five or six different soil moistures ranging from just above residual saturation to saturation), we modeled dissolved contaminant concentration at three different depths and three different time periods. Initial depths modeled were three meters (10 feet), five meters (16 feet), and 15 meters (49 feet).

Concentrations were modeled for one day, 21 days, and 150 days. This equation assumes that the inflow of contaminants is continuous, as opposed to discrete occurrences throughout the season. Therefore, concentration will increase as time increases because there is more inflow of contaminants from the surface. The times modeled represent the time that water would be held in the basin, infiltrating into the subsurface. One day and 21 days much more accurately represent reasonable durations during which the infiltration basin would hold water inside it. Rainfall in Los Angeles occurs within a timeframe of approximately 150 days (between November and April), so modeling 150 days reflects this time period. However, because stormwater infiltrates between storms, it would not actually be present in the basin for that entire length of time. It would be present in the basin on discrete occasions within the 150-day timeframe, corresponding with rainfall occurrences and a short period of time thereafter. Because stormwater would not be infiltrating the soil at all times during this period, the concentrations for this time period are likely to be over-estimated.

RESULTS

We found that, in most cases, the organic contaminants were sorbed and degraded to the point that they did not exceed drinking water standards at the modeled depths and times. Appendix F contains full data on the concentration of each contaminant in water in each soil type at different soil moisture contents, different times, and different depths. Generally, concentrations exceeded the standards when the soil was saturated (the contaminated water was moving through as fast as possible, so there was less time for contaminants to sorb and degrade) and when time was long (150 days).

There were no exceedances of PRGs. Exceedances of MCLs in water in silty clay loam occurred at all depths at the highest pore-water velocity possible (at saturated soil moisture) (see Table 18). The unsaturated hydraulic conductivity of silty clay loam at a soil moisture content of 0.482 is 2.23 centimeters per day. Two contaminants were present in water at the depths that we studied: methlyene chloride and pentachlorophenol. Both have low K_d values of 0.237 and 11.9, respectively, meaning that they will not sorb easily to soil. As a result, they were present in concentrations exceeding their MCLs, despite having fairly short half-lives of 28 and 178 days, respectively. Given sufficient depth, pentachlorophenol sufficiently sorbed or degraded, although methylene chloride was still present at the greatest depth we studied after 150 days. All other contaminants were present in concentrations below their MCL.

Table 18: Concentrations of Contaminants in Excess of MCLs in Water in Silty Clay Loam

Contaminant	Depth (m)	Time (d)	Soil Moisture	Concentration (mg/L)	MCL (mg/L)
Methylene Chloride	3	21	0.482	7.22E-3	5.00E-3
Methylene Chloride	3	150	0.482	9.44E-3	5.00E-3
Methylene Chloride	5	21	0.482	5.24E-3	5.00E-3
Methylene Chloride	5	150	0.482	8.14E-3	5.00E-3
Methylene Chloride	15	150	0.482	5.03E-3	5.00E-3
Pentachlorophenol	3	1	0.482	1.77E-3	1.00E-3
Pentachlorophenol	3	21	0.482	2.00E-3	1.00E-3
Pentachlorophenol	3	150	0.482	4.15E-3	1.00E-3

Exceedances of MCLs or PRGs in water in sandy loam occurred at the highest and second-highest pore-water velocities possible (at saturated and almost-saturated soil moistures) (see Table 19). At a soil moisture content of 0.3, the hydraulic conductivity in sandy loam is 0.416 centimeters per day and increases to 15.5 centimeters per day at a soil moisture content of 0.387. More contaminants were present in water in sandy loam than in silty clay loam due to the much higher hydraulic conductivity of sandy loam at saturation, which allows water and the contaminants it contains to infiltrate more rapidly. Both methylene chloride and pentachlorophenol were present on more occasions than in silty clay loam, because they moved more rapidly though sandy loam and had less chance to sorb or degrade. Bis(2-ethyl-hexyl) phthalate was also present at a shallow depth due to the soil's high hydraulic conductivity, despite its short half-life of 23 days.

Table 19: Concentrations of Contaminants in Excess of MCLs in Water in Sandy Loam

Contaminant	Depth (m)	Time (d)	Soil Moisture	Concentration (mg/L)	MCL (mg/L)
bis(2-Ethylhexyl) phthalate	3	150	0.387	9.30E-3	6.00E-3
Methylene Chloride	3	150	0.3	5.31E-3	5.00E-3
Methylene Chloride	3	21	0.387	1.28E-2	5.00E-3
Methylene Chloride	3	150	0.387	1.30E-2	5.00E-3
Methylene Chloride	5	21	0.387	1.17E-2	5.00E-3
Methylene Chloride	5	150	0.387	1.23E-2	5.00E-3
Methylene Chloride	15	21	0.387	7.83E-3	5.00E-3
Methylene Chloride	15	150	0.387	1.03E-2	5.00E-3
Pentachlorophenol	3	1	0.387	5.85E-3	1.00E-3
Pentachlorophenol	3	21	0.387	7.23E-3	1.00E-3
Pentachlorophenol	3	150	0.387	2.33E-2	1.00E-3
Pentachlorophenol	5	1	0.387	1.50E-3	1.00E-3
Pentachlorophenol	5	21	0.387	1.96E-3	1.00E-3
Pentachlorophenol	5	150	0.387	8.94E-3	1.00E-3

Exceedances of MCLs or PRGs in water in clay loam occurred at the highest and second-highest pore-water velocities possible (at saturated and almost-saturated soil moistures) (see Table 20). The hydraulic conductivity of clay loam is 0.410 centimeters per day at a soil moisture content of 0.4 and 5.00 centimeters per day at a soil moisture content of 0.442. Bis(2-ethylhexyl) phthalate was present at the shallowest depth at the longest time, although its short half-life prevented any other occurrences. Methylene chloride was present at shallower depths at both short and long times, as well as at the deepest depth at 21 and 150 days, due to its small K_d and lack of affinity for adsorption. Pentachlorophenol was present at the shallowest depth at all times, although it was not present at the deepest depth, due to its fairly short half-life.

Table 20: Concentrations of Contaminants in Excess of MCLs in Water in Clay Loam

Contaminant	Depth (m)	Time (d)	Soil Moisture	Concentration (mg/L)	MCL (mg/L)
Methylene Chloride	3	150	0.4	5.06E-3	5.00E-3
Methylene Chloride	3	21	0.442	1.03E-2	5.00E-3
Methylene Chloride	3	150	0.442	1.12E-2	5.00E-3
Methylene Chloride	5	21	0.442	6.08E-3	5.00E-3
Methylene Chloride	5	150	0.442	1.02E-2	5.00E-3
Methylene Chloride	15	150	0.442	7.46E-3	5.00E-3
Pentachlorophenol	3	1	0.442	3.11E-3	1.00E-3
Pentachlorophenol	3	21	0.442	3.60E-3	1.00E-3
Pentachlorophenol	3	150	0.442	9.03E-3	1.00E-3
Pentachlorophenol	5	150	0.442	1.92E-3	1.00E-3

Chrysene was not present above its PRG in water in any soils at any soil moisture contents, depths, or times. Although it has a relatively long half-life (1000 days), it has an extremely high K_d (632.5) and, therefore will sorb rather than move through the soil.

Methylene chloride was the only contaminant present at a depth of 15 meters. Therefore, we calculated the potential for removal of this contaminant in three soil types at depths of 20 meters, 30 meters, and 40 meters. Complete results are shown in Appendix G. In silty clay loam, the MCL for methylene chloride was not exceeded at these depths. However, in water in sandy loam at all three of these depths with saturated soil, methylene chloride was present at these depths at levels above the MCL at times of 21 days and 150 days (see Table 21). This is because the contaminant has such a low K_d value that it will not sorb easily. In fact, because methylene chloride does not tend to sorb, and because sandy loam is such a permeable soil, it would take a depth of 110 meters to reduce methylene chloride to the MCL after a time period of 150 days when the soil is saturated.

Table 21: Concentrations of Methylene Chloride in Excess of MCLs in Water in Sandy Loam

Contaminant	Depth (m)	Time (d)	Soil Moisture	Concentration (mg/L)	MCL (mg/L)
Methylene Chloride	20	21	0.387	7.46E-3	5.00E-3
Methylene Chloride	20	150	0.387	9.64E-3	5.00E-3
Methylene Chloride	30	21	0.387	8.08E-3	5.00E-3
Methylene Chloride	30	150	0.387	8.64E-3	5.00E-3
Methylene Chloride	40	150	0.387	7.88E-3	5.00E-3

In water in clay loam at depths of 20 meters and 30 meters with saturated soil, methylene chloride was present at levels above the MCL at a time of 150 days (see Table 22). Once depth to groundwater has increased to 40 meters, however, methylene chloride was no longer present in water in saturated soils.

Table 22: Concentrations of Methylene Chloride in Excess of MCLs in Water in Clay Loam

Contaminant	Depth (m)	Time (d)	Soil Moisture	Concentration (mg/L)	MCL (mg/L)
Methylene Chloride	20	150	0.442	6.64E-3	5.00E-3
Methylene Chloride	30	150	0.442	5.47E-3	5.00E-3

LIMITATIONS

In addition to previously stated assumptions, there are several limitations to our calculations. First, our equation considered only organic contaminants and only sorption and degradation as contaminant removal processes. Therefore, it cannot be used to model the removal of other contaminants, such as metals, that undergo other processes such as chelation and complexation. In addition, although pathogens may be sorbed and degraded, they cannot be modeled in this equation, as it does not account for death and growth rates and other influencing factors.

Second, we assumed that the soil horizon is homogenous and has the same characteristics and properties throughout. In reality, the soil horizon is heterogeneous, with each layer showing variability in properties that affect contaminant removal. The composition of the gas, solid, and solution phases of the soil in the vadose zone is dynamic, causing spatial and temporal variations in the chemical and biological reactions that transform chemicals. Soil heterogeneity is due to formation processes, tectonic activity, weathering, and chemical and biological processes. It is not appropriate to account for this heterogeneity by using average values for important properties. If the stratigraphy of heterogenous soil is known, this equation could be applied by taking a step-by-step process, changing the appropriate values after calculating the contaminant concentration in each stratum. We assumed that soil moisture content, and therefore unsaturated hydraulic conductivity and pore-water velocity, were constant throughout the soil under each scenario; this is not likely to be the case. Again, more accurate predictions could be made by taking a step-by-step approach after dividing the vadose zone into zones of different soil moisture content, an effort that is made more complicated by the dynamic nature of soil moisture.

Third, we assumed that all of the movement of water is within soil pores. This may not be true, however, especially in the upper few feet of the soil, which may contain macropores or larger channels such as root paths or holes created by biota (e.g., worm holes). If macropores or large channels are present, water could then bypass the soil pores and travel rapidly through the macropores instead, significantly reducing the time that the water is held within the soil matrix. This could lead to excessive concentrations of contaminants in groundwater, as rapid infiltration provides less time for adsorption and biodegradation. Since our equation did not make allowances for this rapid travel, actual contaminant concentrations could be much different if water moves through a larger flowpath.

Fourth, we addressed the effects of the soil on each contaminant individually. We could not determine the effects of the soil on the contaminants together, as the equation did not account for the simultaneous presence of another contaminant. It is possible that each additional contaminant may have a negative effect on the removal of another, causing concentrations to be much larger than predicted. It is also possible that contaminants may have positive interactive effects, or none at all. We did not have the capability to examine any interactive effects. In addition, we did not consider the formation and subsequent removal of degradation byproducts that could form when the main contaminants were broken down.

Fifth, we did not account for the change in the soil's removal capability over time, as these contaminants will accumulate in the soil. It is possible that, after receiving a certain amount of stormwater contaminants, the soil will lose its capacity to adsorb. Also, we did not account for differences in removal efficiency predicted by the equation and removal efficiency observed in the natural environment. Because actual infiltration basins are in a natural setting, the processes by which removal occurs are not completely efficient. Not all contaminants will be removed or degraded to the extent predicted by the equation.

CONCLUSION

In silty clay loam, under all times and soil moisture contents studied, bis(2-ethylhexyl) phthalate, chlordane, and chrysene were adequately removed in a soil depth of three meters (10 feet), while pentachlorophenol required five meters (16 feet) and methylene chloride required 20 meters (66 feet). In sandy loam, chlordane and chrysene were sufficiently reduced in a soil depth of three meters (10 feet); bis(2-ethylhexyl) phthalate in a depth of five meters (16 feet); pentachlorophenol in a depth of fifteen meters (50 feet); and methylene chloride in a depth of 110 meters (361 feet). In day loam, a soil depth of three meters (10 feet) was required to reduce bis(2-ethylhexyl) phthalate, chlordane, and chrysene to necessary levels; a depth of fifteen meters (50 feet) was required for pentachlorophenol; and a depth of 40 meters (131 feet) for methylene chloride.

Based on our assumptions and these calculations, we conclude that infiltration of stormwater containing the contaminants that we studied would not contaminate groundwater given a certain depth to the aquifer. This depth varies depending on soil type and soil moisture content. Although we analyzed the decrease in contaminant concentrations using various soil moisture contents and times, the most conservative assumption was that the soil is saturated, as water infiltrating the subsurface moves most rapidly through saturated soil, and that time is 150 days, as that is the longest time period during which there could be substantial rainfall. Therefore, a minimum depth to groundwater was set equal to the depth required to adequately reduce contaminant concentrations after a time period of 150 days when the soil is saturated.

In all three soils, methylene chloride was the contaminant that required the greatest depth for adequate reduction in concentration. In silty clay loam, under saturated conditions and with a time period of 150 days, this depth was 20 meters (66 feet); in sandy loam, 110 meters (361 feet); and in clay loam, 40 meters (131 feet). These depths are likely to be over-estimated because it is improbable that the soil will be saturated throughout the entire soil column during the entire 150-day time period. We conclude that, given the presence of these stormwater contaminants and concentrations, an infiltration basin could be placed in any of the three predominant soil types in the San Fernando Valley provided that these depths to groundwater are met.

Once we determined the conditions under which groundwater would not be contaminated by stormwater infiltration, we analyzed the costs and benefits of using infiltration basins to recharge groundwater. Our cost-effectiveness analysis is presented in the next section.

COST-EFFECTIVENESS OF INFILTRATION BASINS

INTRODUCTION

We have ascertained that the volume of water available for capture from a five-acre drainage area ranges between 0.90 AF per year and 1.87 AF per year, depending on infiltration basin size and the infiltration rate of the soil. We have also concluded that given sufficient depth to groundwater, contaminant concentrations will be reduced to acceptable levels (MCLs or PRGs) as they move through the soil. However, the feasibility of using an infiltration basin to capture stormwater runoff for groundwater recharge depends not only on the volume of water captured by an infiltration basin and the proportion of contaminants removed, but also on the project's cost-effectiveness.

A project is determined to be cost-effective if its expected value exceeds its costs. In this case, that occurs if the costs of an infiltration basin are less than the current value of drinking water. Costs include land acquisition, construction, operation and maintenance, and groundwater pumping, treatment, and distribution. The costs of construction and operation and maintenance are related to the size of the infiltration basin; therefore, they vary with basin size. The costs of pumping, treating, and distributing groundwater are dependent upon the volume of infiltrated water, so they also vary with basin size.

We calculated the cost per AF of infiltrated water associated with each of the four basin sizes, 0.1 acre and 0.5 acre with depths of two feet and three feet. We then compared this cost to the current price of the next alternative source, or marginal source, of drinking water. Should the City's current drinking water supplies become inadequate, its next option is to import additional water from MWD, which is available at a price of $431/AF (Mackowski, 2001).

It should be noted that the costs presented here are general, but adequate for planning purposes. The costs do not account for any contingencies involved in planning, design, and administration, nor do they include legal and permitting fees, costs of geotechnical testing, or engineering expenses.

COSTS OF INFILTRATION BASINS

Land acquisition costs can vary greatly from site to site, making it perhaps the greatest variable influencing overall costs (EPA, 1999b). The price of land in the San Fernando Valley varies with the total square footage[4] of the lot. For example,

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[4] One acre equals 43,560 square feet.

lots that total around 5,000 square feet cost about $20 per square foot. Lots greater than 10,000 square feet cost between $12 and $15 per square foot (County of Los Angeles, Office of the Assessor, 2001).

The actual area of land necessary to construct an infiltration basin is greater than the size of the basin itself, because additional land around the perimeter of the basin is needed. Therefore, we added 20% to the surface area of each basin to determine how much land must be purchased. The 0.1-acre basin has a surface area of 4,356 square feet; increasing the surface area by 20% yields a size of 5,227 square feet. The 0.5-acre basin has a surface area of 21,780 square feet, and increasing this surface area by 20% results in a necessary purchase of 26,136 square feet. Because the 0.1-acre basin has an area less than 10,000 square feet, we used $20 per square foot to calculate the cost of land. We used a conservative value of $15 per square foot to calculate the cost of land for the 0.5-acre basin, since it is larger than 10,000 square feet. Given these numbers, the total land cost for the 0.1-acre basin is $104,560, and the total land cost for the 0.5-acre basin is $326,700.

Using the following equation (Schueler, 1987), we determined the costs of constructing the four sizes of infiltration basins, based on their surface areas and depths:

Cost (in 1985 dollars) = $10.7 \cdot V^{0.69}$, where

V = total basin volume (cubic feet).

This equation was developed over a decade ago, and there have been few recent studies on construction costs. However, it was cited as recently as 1999 in an EPA (1999b) report. Since the costs used to develop the equation were in 1985 dollars, we adjusted our results for inflation to 2001 dollars (Bureau of Labor Statistics, 2001).

Because infiltration basins exhibit economies of scale with regard to construction costs, the above equation is applicable to infiltration basins with a volume larger than 10,000 cubic feet in size (Schueler, 1987). Three of the basin sizes had volumes larger than this; the 0.1-acre basin with a depth of two feet has a smaller volume of 7,841 cubic feet, given on our prior assumption that there is a ratio of 1:0.8 between the surface area and the bottom area of the basin. Despite this smaller size, we applied the equation to this basin for purposes of consistency.

The maintenance of infiltration basins is essential for effective operation and typically includes inspection, debris and litter removal, erosion control, and sediment removal. Operation and maintenance costs have been estimated at 3-5% of the basin's initial construction costs (excluding land acquisition) (Schueler, 1987). Since construction costs depend on basin size, operation and maintenance costs also depend on basin size. To be conservative, we assumed that these costs would be 5% of construction costs.

It is also necessary to include the costs of pumping the infiltrated stormwater once it has reached the aquifer, as it must be retrieved from the ground before it has value as drinking water. Additionally, we included the costs of treatment and distribution of groundwater. Despite our previous findings that drinking water MCLs could be met when infiltration basins are placed in areas that have sufficient depth to groundwater, it is necessary that groundwater undergo the treatment process before it is distributed. Together, the costs of pumping, treatment, and distribution total around $100 per AF in current dollar values (Mackowski, 2000). We assumed that existing groundwater pumping facilities would be used, so it is not necessary to consider any additional capital costs for constructing this infrastructure. In addition, we assumed that all water captured by infiltration basins would infiltrate into groundwater and not evaporate or move laterally away from the groundwater basin. The total costs for each basin size are shown in Table 23.

Table 23: Costs of Infiltration Basins

Basin Size (acre)	**0.1**		**0.5**	
Type of Cost	**Depth (ft)**		**Depth (ft)**	
	2	**3**	**2**	**3**
Land Costs ($)	104,560	104,560	326,700	326,700
Construction Costs ($)	9,110	12,052	27,660	36,589
Operation and Maintenance Costs ($/yr)	456	603	1,383	1,829
Pumping, Treatment, and Distribution Costs ($/AF)	100	100	100	100
Total	114,226	117,315	355,843	365,218

VALUE OF INFILTRATED WATER

The value of the additional drinking water supplies that would result from this project is derived from the value of the next additional source, or marginal source, of drinking water for Los Angeles. By 2015, the City of Los Angeles is predicted to have increased its proportion of water delivered by MWD from the current 20% during normal water years to 45% (MWD, 2001). Since water delivered by MWD is the next available source, its value is a good proxy for the value of the recharged water resulting from this project. The current value of an additional AF of treated water from MWD is $431 (MWD, 2001), which includes the cost of treating the water to meet MCLs. Therefore, this drinking water source is comparable to pumped, treated groundwater that results from infiltrated stormwater.

COST PER ACRE-FOOT OF INFILTRATED WATER

We calculated the cost per AF of water resulting from each infiltration basin over its estimated lifetime to determine how this management alternative would be valued today, assuming an operation period of 25 years. We expected that land acquisition and construction costs were incurred at the beginning of the project (i.e., the beginning of year 0) and that pumping of groundwater first happened at the beginning of year 1. Even though it would take time for infiltrated stormwater to actually recharge the aquifer, pumping could occur now in anticipation of future recharge.

We also anticipated that at the end of 25 years, the land could be returned to its previous condition; that is, the land has a salvage value equal to its original purchase price. To obtain in today's dollars the value of the land 25 years in the future (i.e., the salvage value), the purchase price was discounted over this time period using a real discount rate of 4.2% (The White House Office of Management and Budget, 2000), which accounts for any effects of inflation. Because land acquisition and construction costs are one-time costs occurring at the beginning of the project, these costs were added upfront to the present value of the salvaged land to give the present value of the capital (see Table 24).

Table 24: Cost of Land, Salvage Value of Land, and Present Value of Capital

Basin Size (acre)	Cost of Land ($)	Salvage Value ($)	Present Value ($)	
			Basin Depth (ft)	
			2	3
0.1	104,560	37,383	76,287	79,229
0.5	326,700	116,804	237,556	246,485

Note: Values are in 2001 dollars.

The results of the volume analysis discussed earlier for each basin scenario yielded an amount of water in AF per year; however, capital costs are in dollars and operation and maintenance costs are in dollars per year. Since our objective was to compare the cost per AF of water to the current value of water provided by MWD (in dollars per AF), we annualized the present value of the capital to provide a value in dollars per year. We used a 25-year annuity factor for a 4% interest rate (closest to the 4.2% rate we used to discount the salvage value above), which is 15.62 (Brealy et al, 1998). We then added the costs of operation and maintenance and groundwater pumping, treatment, and distribution (adjusted for number of AF per year) to the annualized present value of the capital to yield the total cost of the project per year. Next, we divided this by the volume of water infiltrated each year to provide the cost of the project in dollars per AF of infiltrated water, which is shown in Table 25.

Table 25: Cost Per Acre-Foot of Infiltrated Water Resulting From Each Basin Scenario

Basin Size (acre)	**0.1**		**0.5**	
Infiltration Rate (in/hr)	**Basin Depth (ft)**		**Basin Depth (ft)**	
	2	**3**	**2**	**3**
0.5	$6,033	$5,259	$9,803	$9,517
1.0	$5,662	$5,035	$9,690	$9,517
2.0	$5,662	$4,910	$8,972	$9,517

It is apparent from these results that the cost per AF of water, given the parameters identified in our study, is much greater than the value of the water produced ($431/AF). Thus, stormwater infiltration is not a cost-effective method of increasing drinking water supplies in Los Angeles.

However, it is possible to reduce or eliminate the cost of land acquisition (and therefore the overall cost of infiltrated water) by designing the infiltration basin as a multi-use facility incorporated into existing open space. As such, it can serve multiple functions, including both recharge and recreation (see Figure 16). We have included a cost analysis of this situation to illustrate the difference in the cost of infiltrated water when land is not considered. Our study does not fully explore the feasibility of multiple-use infiltration basins in the San Fernando Valley, but it is nonetheless useful to present the results, given that land acquisition is the most expensive and most variable cost.

Without land acquisition costs, it was necessary to annualize only the upfront construction costs, using the same annuity factor we used earlier (15.62). Then, as before, we added the operation and maintenance costs and pumping costs to this annualized value and divided by the number of acre-feet of water produced per year. This greatly reduced the cost per AF of water from this recharge method, as shown in Table 26. Nonetheless, even without the costs of land acquisition, the cost per AF of infiltrated water greatly exceeds the value of water.

Table 26: Cost Per Acre-Foot of Infiltrated Water Resulting From Each Basin Scenario (Excluding Land Acquisition)

Basin Size (acre)	**0.1**		**0.5**	
Infiltration Rate (in/hr)	**Basin Depth (ft)**		**Basin Depth (ft)**	
	2	**3**	**2**	**3**
0.5	$1,255	$1,350	$1,944	$2,311
1.0	$1,183	$1,295	$1,923	$2,311
2.0	$1,183	$1,265	$1,787	$2,311

Figure 16: Multiple-Purpose Infiltration Basin

CONCLUSION

Our analysis shows that infiltration basins of the sizes we considered are not a cost-effective option for the recharge of groundwater with stormwater runoff, based on our assumptions about the costs of land acquisition, construction, and operation and maintenance. Even without the large capital cost of land, the volume of water that can be captured with these basins and the current value of water are not great enough to justify such a project. Water would have to be valued at a minimum of $1,183 per AF to make even one of the presented scenarios cost-effective.

Our cost-effectiveness analysis focused on the value of stormwater infiltration solely as a method of augmenting drinking water supplies. However, stormwater regulations are becoming more stringent, and municipalities are being forced to better manage their stormwater by methods such as infiltration basins. If the value of infiltration as a stormwater management strategy is taken into consideration in a cost-effectiveness analysis, infiltration basins may become cost-effective.

For example, infiltration basins that capture stormwater runoff play a role in flood control by limiting the volume and force of runoff, thereby reducing damage caused by flooding. Also, capturing and infiltrating stormwater runoff reduces the amount of contaminants entering streams and the ocean and lessens the impacts on these aquatic ecosystems. Consequently, infiltration basins may provide benefits in terms of reduced costs of compliance with stormwater permits or TMDLs. In addition, bacteria associated with stormwater runoff have resulted in beach closures due to human health risks. By retaining and infiltrating stormwater, infiltration basins reduce the amount of runoff reaching the ocean and may reduce the risk of beach closures.

It may also be possible to transfer the costs associated with infiltration basins from public agencies to private developers, who are required by existing regulations to mitigate stormwater runoff from developments. Pursuant to provisions within the NPDES permit under the Clean Water Act, Los Angeles County submitted a Standard Urban Stormwater Mitigation Plan (SUSMP) that addresses stormwater contamination from new developments and redevelopment by the private sector (LARWQCB, 2000). The SUSMP designates best management practices (BMPs) that must be used in seven categories of development projects, including: 100-plus home subdivisions; 10-plus home subdivisions; 100,000-plus square foot commercial developments; and hillside single-family dwellings. Developers are responsible for mitigating stormwater runoff either through treatment or infiltration of stormwater and for all costs of complying with the SUSMP. Therefore, groundwater recharge can potentially occur through infiltration basins paid for and constructed by a developer in order to comply with the SUSMP, rather than by the implementing public agency.

The costs in this situation cannot be ignored just because they are not borne by a public agency. Nonetheless, agencies can take advantage of the groundwater recharge that may occur through the requirement that developers mitigate stormwater runoff through the SUSMP. In addition, the accompanying benefits of this method as a stormwater management strategy could be quantified and incorporated into a cost-effectiveness analysis, thus increasing the cost-effectiveness of the infiltration basins. However, the analysis of these considerations was beyond the scope of this project.

CONCLUSIONS AND RECOMMENDATIONS

Our study explored the use of infiltration basins that capture urban stormwater runoff as a means of increasing the reliability of local groundwater resources used for drinking water in the San Fernando Valley of Los Angeles County. We first determined the volume of runoff that could be captured by infiltration basins using a calculation based on empirical studies. Model-based predictions were then used to evaluate the depth of soil necessary to sufficiently reduce stormwater contaminants in three different soil types. Finally, we analyzed the cost-effectiveness of this management option by comparing costs of infiltration basins with the value of recharged groundwater, equivalent to the value of the marginal source of drinking water.

Our analysis established that an infiltration basin with a surface area of 0.1 acre and depths of two feet or three feet could capture from 0.90 to 01.18 AF per year, depending on the infiltration rate of the underlying soil. An infiltration basin with a surface area of 0.5 acre and depths of two feet or three feet can capture from 1.71 to 1.87 AF per year, depending on infiltration rate. Volumes were assumed to be captured from a five-acre drainage area with land use distribution representative of the San Fernando Valley. Our results indicated that smaller basins capture stormwater runoff more efficiently than larger basins, which is significant in the overall evaluation of this strategy, since the smaller the basin, the easier it is to place in an urban area.

In order for stormwater contaminants to be adequately reduced from typical concentrations to the Maximum Contaminant Levels set for drinking water, we found that necessary depths to groundwater are 66 feet in silty clay loam, 361 feet in sandy loam, and 131 feet in clay loam. These depths are based on the presence of methylene chloride, a contaminant that does not adsorb easily and therefore requires a greater depth of soil for its removal. All other contaminants were removed by a depth of 50 feet.

We also determined that infiltration basins are not a cost-effective method of increasing drinking water supplies. The costs associated with land acquisition, construction, and operation and maintenance of infiltration basins far exceed the value of the drinking water they would provide. In order for any of the four basin sizes that we analyzed to be cost-effective, water must be valued at greater than $1,183 per AF. However, our cost-effectiveness analysis focused on the value of stormwater infiltration solely as a method of augmenting drinking water supplies. Infiltration basins also have value as a stormwater management strategy, the benefits of which may be quantified and incorporated into a cost-effectiveness analysis, thereby increasing the cost-effectiveness of such a project. The analysis of these considerations was beyond the scope of this project.

We also did not consider certain aspects that must be examined by agencies considering this management option. For example, bacteria in stormwater runoff may pose a health risk if allowed to infiltrate into groundwater used for drinking water. Contaminants may accumulate both on the surface of the infiltration basin and within the underlying soil. In addition, public reaction to this type of project may not be positive. These aspects were also beyond the scope of our project, and we recommend that they be studied.

In addition, we recommend that stormwater runoff in Los Angeles be sampled and monitored more thoroughly to provide a more accurate depiction of the types and amounts of contaminants. If infiltration basins are implemented for groundwater recharge, we also recommend monitoring for the presence of contaminants in groundwater and the accumulation of contaminants in the surface and underlying soils of the basin.

The analyses, discussions, results, and recommendations presented here will be beneficial to agencies and individuals considering the use of stormwater infiltration basins to recharge groundwater used for drinking water. Our study also provides a basis of discussion for those interested in stormwater infiltration as a stormwater management strategy.

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APPENDICES

APPENDIX A: WATER IMPORTED INTO ULARA (1969-1990)

Year	Imported Water (AF)		
	LA-Owens	MWD	Combined
1969	335,235	28,500	363,735
1970	377,320	27,623	404,943
1971	478,535	24,866	503,401
1972	452,867	28,929	481,796
1973	447,034	28,344	475,378
1974	435,011	22,080	457,091
1975	433,683	22,940	456,623
1976	443,778	54,446	498,224
1977	296,101	49,468	345,569
1978	399,797	48,142	447,939
1979	464,701	51,089	515,790
1980	470,224	57,508	527,732
1981	458,178	56,170	514,348
1982	461,579	59,017	520,596
1983	444,017	59,761	503,778
1984	489,717	65,758	555,475
1985	584,835	64,809	649,644
1986	584,660	64,664	649,324
1987	589,945	68,888	658,663
1988	562,644	76,972	639,616
1989	554,502	81,517	636,019
1990	142,707	470,202	612,909

Source: Blomquist, 1992.

APPENDIX B: ULARA GROUNDWATER EXTRACTIONS (1969-1990)

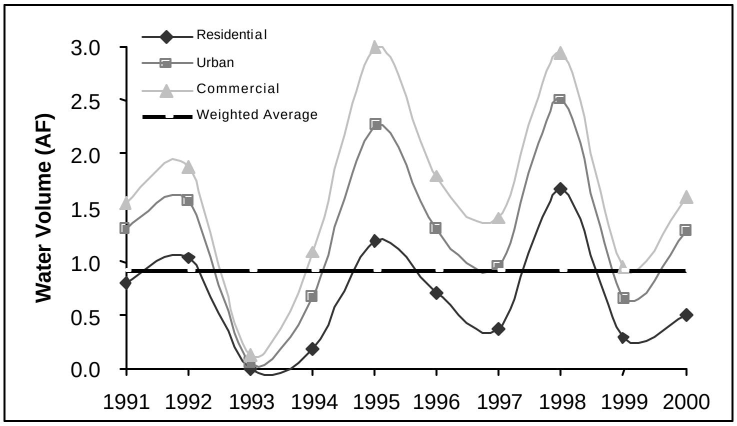
Year	Groundwater Extractions (AF)	
	San Fernando	ULARA Total
1969	91,785	104,070
1970	96,290	109,618
1971	85,936	96,556
1972	91,376	104,181
1973	88,770	100,906
1974	92,867	105,208
1975	100,373	111,966
1976	108,457	119,975
1977	129,439	140,019
1978	70,543	81,398
1979	64,645	75,483
1980	63,337	72,925
1981	97,789	109,730
1982	87,675	100,237
1983	71,312	82,855
1984	119,560	132,299
1985	105,782	118,151
1986	90,833	102,752
1987	96,604	107,788
1988	109,624	120,100
1989	132,581	142,559
1990	86,898	96,689

Source: Blomquist, 1992.

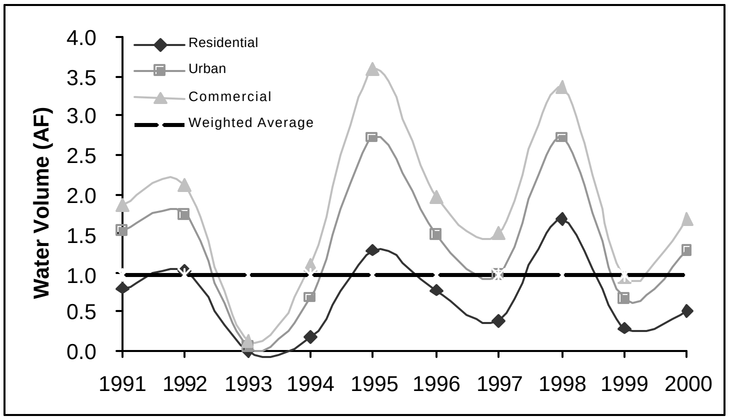
APPENDIX C: VOLUME OF WATER CAPTURED PER YEAR

Volume of Water Captured Per Year In A 0.1-Acre Basin

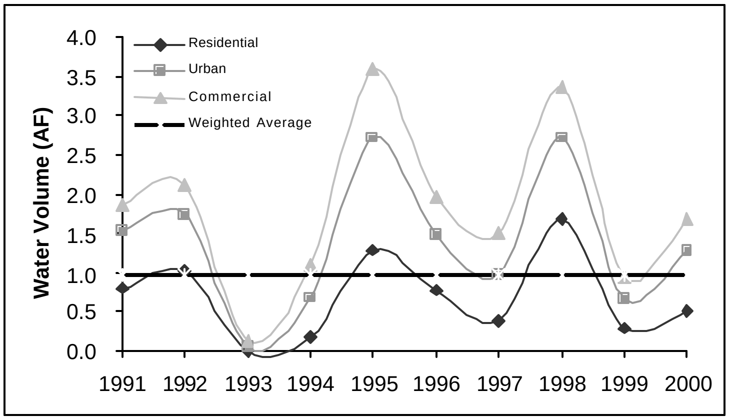
DEPTH= 2 FEET, INFILTRATION RATE =0.5 INCH/HOUR



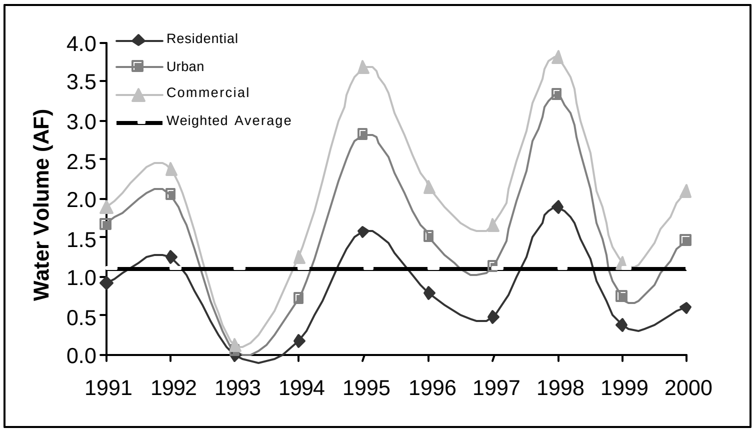
DEPTH = 2 FEET, INFILTRATION RATE =1.0 INCH/HOUR



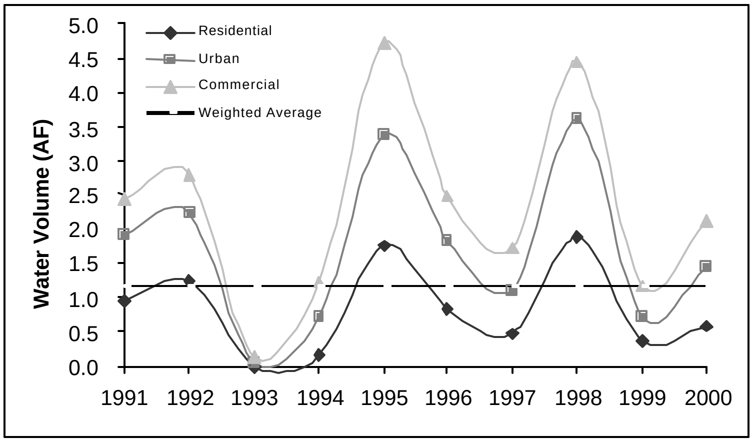
DEPTH = 2 FEET, INFILTRATION RATE =2.0 INCHES/HOUR



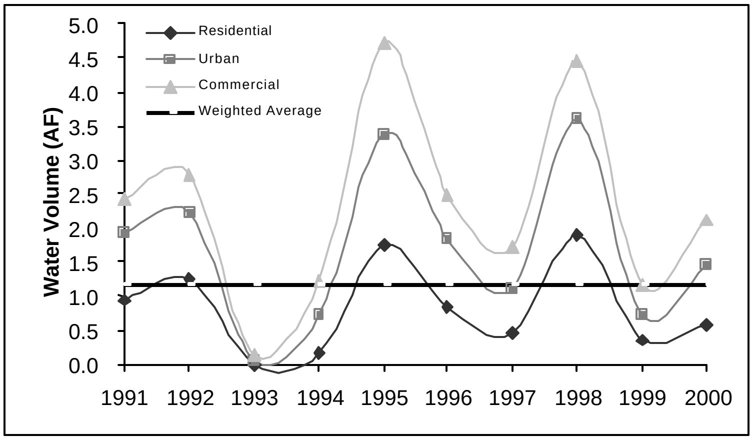
DEPTH = 3 FEET, INFILTRATION RATE =0.5 INCH/HOUR



DEPTH = 3 FEET, INFILTRATION RATE = 1.0 INCH/HOUR

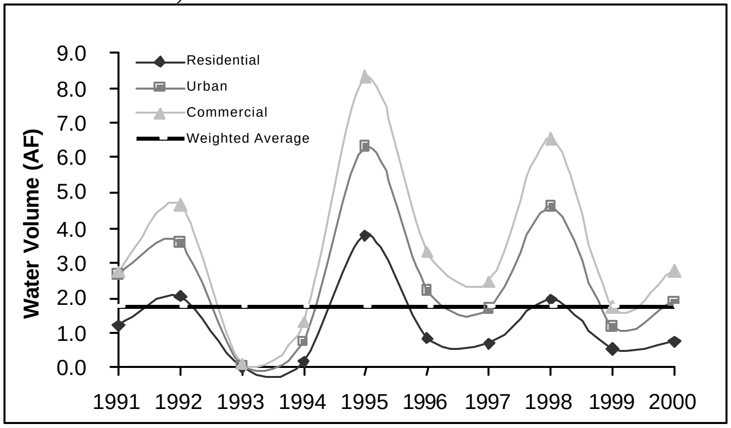


DEPTH = 3 FEET, INFILTRATION RATE = 2.0 INCHES/HOUR

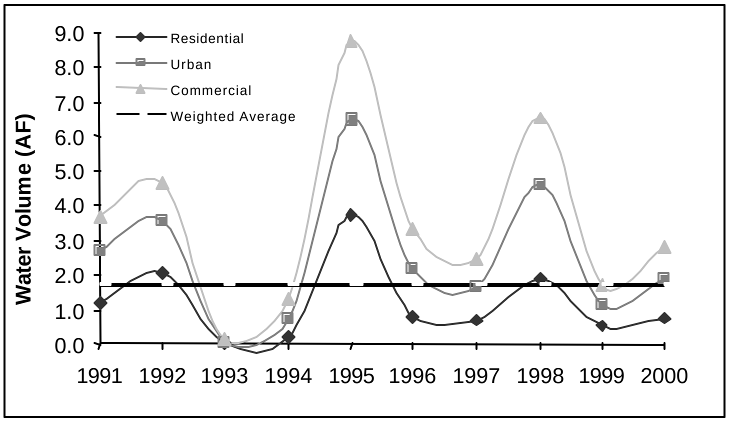


Volume of Water Captured Per Year In A 0.5-Acre Basin

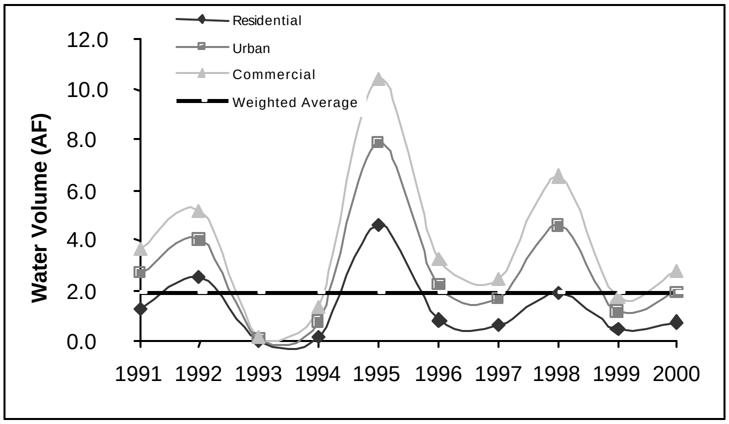
DEPTH = 2 FEET, INFILTRATION RATE = 0.5 INCH/HOUR



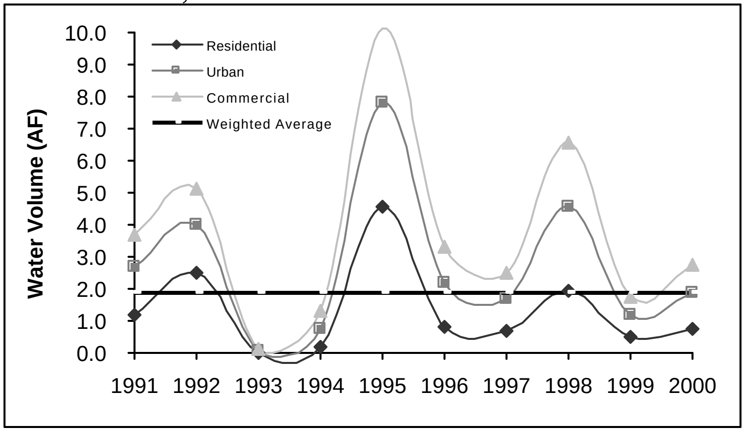
DEPTH= 2 FEET INFILTRATION RATE =1.0 INCH/HOUR



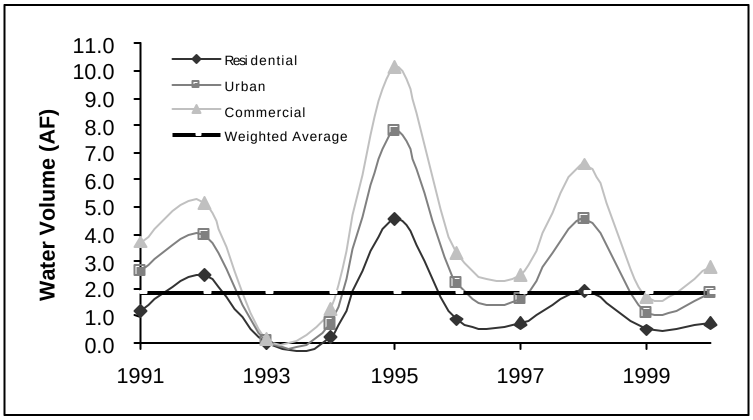
DEPTH = 2 FEET INFILTRATION RATE =2.0 INCHES/HOUR



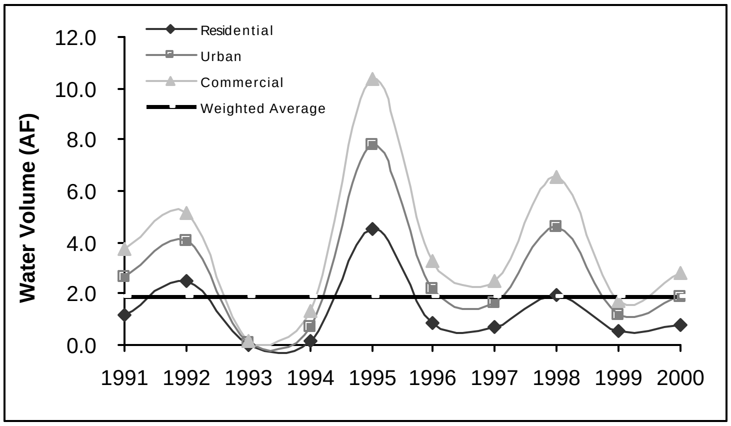
DEPTH = 3 FEET, INFILTRATION RATE =0.5 INCH/HOUR



DEPTH = 3 FEET, INFILTRATION RATE =1.0 INCH/HOUR



DEPTH = 3 FEET, INFILTRATION RATE =2.0 INCHES/HOUR



APPENDIX D: LOS ANGELES COUNTY STORMWATER DATA

Table 4-15e

Seasonal EMCs
1998-99 Storm Season

GROUP	Constituent	Unit	High Density Residential	Light Industrial	Vacant	Retail/ Commercial	Multi-family Residential	Transportation	Education	Mixed Residential
GENERAL MINERALS	Dissolved Phosphorus	mg/ℓ	n/m	0.25	n/m	0.40	0.50	0.47	0.34	0.19
	Kjeldahl-N	mg/ℓ	n/m	3.36	0.65	5.59	3.51	2.45	2.13	5.14
	NH3-N	mg/ℓ	n/m	0.37	n/m	3.39	1.04	0.18	n/m	0.96
	Nitrate-N	mg/ℓ	n/m	0.74	0.53	0.59	2.13	0.96	0.91	0.90
	Nitrite-N	mg/ℓ	n/m	0.08	n/m	0.17	0.17	0.11	0.06	0.10
	Suspended Solids	mg/ℓ	n/m	182.18	12.35	78.91	93.79	75.12	46.67	67.61
	Total Phosphorus	mg/ℓ	n/m	0.30	n/m	0.48	0.58	0.49	0.42	0.28
HEAVY METALS (DISSOLVED)	Dissolved Cadmium	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m	n/m	n/m
	Dissolved Chromium	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m	n/m	n/m
	Dissolved Copper	µg/ℓ	n/m	12.39	n/m	14.86	6.93	35.04	20.48	12.82
	Dissolved Lead	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m	n/m	n/m
	Dissolved Mercury	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m	n/m	n/m
	Dissolved Nickel	µg/ℓ	n/m	3.29	n/m	n/m	n/m	4.04	n/m	n/m
	Dissolved Selenium	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m	n/m	n/m
	Dissolved Silver	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m	n/m	n/m
	Dissolved Zinc	µg/ℓ	n/m	391.05	n/m	182.58	111.38	226.95	95.87	114.94
HEAVY METALS (TOTAL)	Total Cadmium	µg/ℓ	n/m	n/m	n/m	n/m	n/m	0.86	n/m	n/m
	Total Chromium +6	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m	n/m	n/m
	Total Copper	µg/ℓ	n/m	22.18	n/m	28.45	12.68	47.75	25.70	17.53
	Total Lead	µg/ℓ	n/m	6.22	n/m	5.97	n/m	5.50	n/m	3.67
	Total Mercury	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m	n/m	n/m
	Total Nickel	µg/ℓ	n/m	5.06	n/m	4.14	6.95	7.71	n/m	n/m
	Total Selenium	µg/ℓ	n/m	n/m	n/m	n/m	n/m	4.16	n/m	n/m
	Total Silver	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m	n/m	n/m
	Total Zinc	µg/ℓ	n/m	413.69	n/m	252.03	161.12	288.33	127.33	150.00
MISCELLANEOUS	Cyanide	mg/ℓ			n/m					
	Oil and Grease	mg/ℓ			n/m					
	Total Petroleum Hydrocarbons	mg/ℓ			n/m					
	Total Phenols	mg/ℓ			n/m					

Notes:
n/m : Not meaningful, not enough data above detection limit
Blank cells: No data available

Seasonal EMCs
1998-99 Storm Season (cont'd)

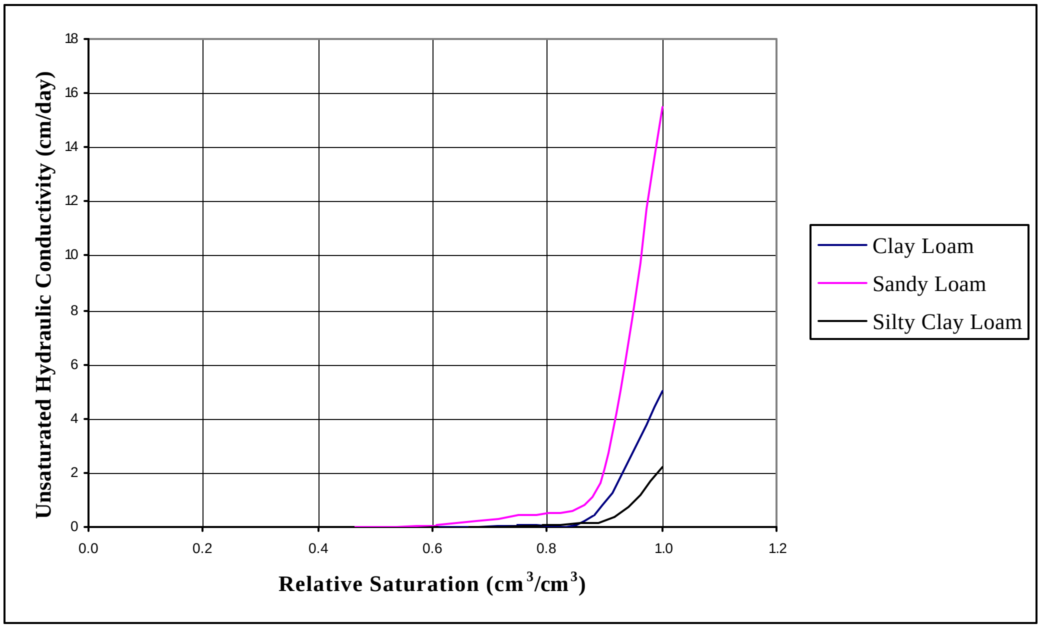
GROUP	Constituent	Unit	High Density Residential	Light Industrial	Vacant	Retail/ Commercial	Multi-family Residential	Transportation	Education	Mixed Residential
BACTERIA	Fecal Coliform	MPN/100mℓ			501.12					
	Fecal Enterococcus	MPN/100mℓ			1156.96					
	Fecal Streptococcus	MPN/100mℓ			1156.96					
	Total Coliform	MPN/100mℓ			2364.56					
PESTICIDES	Chlordane	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Chlorpyrifos	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m	n/m	n/m
	Diazinon	µg/ℓ	n/m	n/m	n/m	0.32	n/m	n/m	n/m	11.90
	Malathion	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m	n/m	n/m
	p,p' DDT	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	PCB-1016	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	PCB-1221	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	PCB-1232	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	PCB-1242	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	PCB-1248	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	PCB-1254	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	PCB-1260	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Simazine	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m	n/m	n/m
SEMIVOLATILES	Acenaphthene	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Acenaphthylene	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Antracene	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Benzo(a)anthracene	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Benzo(a)pyrene	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Benzo(b)fluorant	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Benzo(k)fluorant	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Chrysene	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Dibenz(a,h)anthrecene	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Fluoranthene	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Fluorene	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Indeno (1,2,3-cd) pyrene	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Naphthalene	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Phenanthrene	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m
	Pyrene	µg/ℓ	n/m	n/m	n/m	n/m	n/m	n/m		n/m

Notes:
n/m : Not meaningful, not enough data above detection limit
Blank cells: No data available

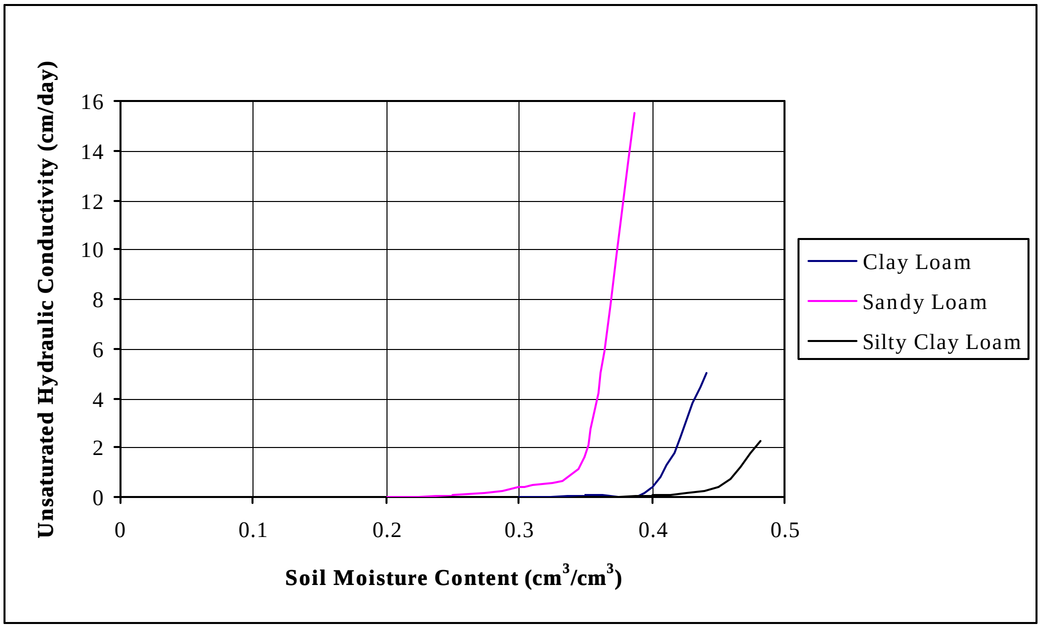
Source: LACDPW, 1999

APPENDIX E: UNSATURATED HYDRAULIC CONDUCTIVITIES OF THREE SOIL TYPES

Unsaturated Hydraulic Conductivities of Three Soil Types Based on Relative Saturation



Unsaturated Hydraulic Conductivities of Three Soil Types Based on Soil Moisture Content



APPENDIX F: CONCENTRATIONS OF CONTAMINANTS IN WATER IN THREE SOIL TYPES

SILTY CLAY LOAM			Time: 1d		Time: 21d		Time: 150d	
Chlordane	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.002mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 3m	0.2	1.92E-04	2.99E-17	2.99E-19	2.99E-17	2.99E-19	2.99E-17	2.99E-19
	0.3	8.38E-03	1.09E-04	1.09E-06	1.09E-04	1.09E-06	1.09E-04	1.09E-06
	0.4	1.05E-01	5.06E-03	5.06E-05	5.06E-03	5.06E-05	5.42E-03	5.42E-05
	0.482	2.23E+00	2.76E-02	2.76E-04	2.94E-02	2.94E-04	4.19E-02	4.19E-04
Chlordane	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.002mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 5m	0.2	1.92E-04	1.90E-23	1.90E-25	1.90E-23	1.90E-25	1.90E-23	1.90E-25
	0.3	8.38E-03	3.53E-07	3.53E-09	3.53E-07	3.53E-09	3.53E-07	3.53E-09
	0.4	1.05E-01	7.45E-05	7.45E-07	7.45E-05	7.45E-07	8.64E-05	8.64E-07
	0.482	2.23E+00	2.30E-03	2.30E-05	2.50E-03	2.50E-05	4.28E-03	4.28E-05
Chlordane	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.002mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 15m	0.2	1.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	8.38E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.4	1.05E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.482	2.23E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Methylene Chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 3m	0.2	1.92E-04	1.43E-21	2.14E-23	1.59E-21	2.38E-23	2.44E-21	3.66E-23
	0.3	8.38E-03	1.65E-05	2.47E-07	2.51E-05	3.76E-07	2.04E-04	3.06E-06
	0.4	1.05E-01	4.37E-03	6.56E-05	1.40E-02	2.09E-04	1.13E-01	1.70E-03
	0.482	2.23E+00	8.69E-02	1.30E-03	4.81E-01	7.22E-03	6.29E-01	9.44E-03

Methylene Chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 5m	0.2	1.92E-04	5.60E-29	8.39E-31	6.60E-29	9.90E-31	1.56E-28	2.33E-30
	0.3	8.38E-03	5.38E-08	8.07E-10	1.22E-07	1.82E-09	6.54E-06	9.81E-08
	0.4	1.05E-01	2.23E-04	3.35E-06	1.46E-03	2.20E-05	5.91E-02	8.86E-04
	0.482	2.23E+00	4.16E-02	6.24E-04	3.49E-01	5.24E-03	5.43E-01	8.14E-03

Methylene Chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 15m	0.2	1.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	8.38E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.4	1.05E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.51E-03	8.26E-05
	0.482	2.23E+00	6.76E-03	1.01E-04	9.11E-02	1.37E-03	3.35E-01	5.03E-03

Pentachlorophenol	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.115mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.001mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 3m	0.2	1.92E-04	1.87E-44	2.15E-45	1.87E-44	2.15E-45	1.87E-44	2.15E-45
	0.3	8.38E-03	7.99E-09	9.19E-10	7.99E-09	9.19E-10	8.34E-09	9.60E-10
	0.4	1.05E-01	3.42E-04	3.93E-05	3.54E-04	4.07E-05	4.18E-04	4.81E-05
	0.482	2.23E+00	1.54E-02	1.77E-03	1.74E-02	2.00E-03	3.61E-02	4.15E-03

Pentachlorophenol	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.115mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.001mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 5m	0.2	1.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	8.38E-03	1.64E-11	1.89E-12	1.64E-11	1.89E-12	1.83E-12	2.10E-13
	0.4	1.05E-01	2.18E-06	2.50E-07	2.30E-06	2.64E-07	3.25E-06	3.74E-07
	0.482	2.23E+00	1.08E-03	1.24E-04	1.28E-03	1.47E-04	4.15E-03	4.78E-04

Pentachlorophenol	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.115mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.001mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 15m	0.2	1.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	8.38E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.4	1.05E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.482	2.23E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Chrysene	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.0092mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 3m	0.2	1.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	8.38E-03	7.25E-22	7.25E-24	7.25E-22	7.25E-24	7.25E-22	7.25E-24
	0.4	1.05E-01	6.13E-08	6.13E-10	6.13E-08	6.13E-10	6.13E-08	6.13E-10
	0.482	2.23E+00	1.32E-03	1.32E-05	1.32E-03	1.32E-05	1.32E-03	1.32E-05

Chrysene	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.0092mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 5m	0.2	1.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	8.38E-03	2.10E-29	2.10E-31	2.10E-29	2.10E-31	2.10E-29	2.10E-31
	0.4	1.05E-01	2.00E-11	2.00E-13	2.00E-11	2.00E-13	2.00E-11	2.00E-13
	0.482	2.23E+00	1.06E-05	1.06E-07	1.06E-05	1.06E-07	1.06E-05	1.06E-07

Chrysene	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.0092mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 15m	0.2	1.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	8.38E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.4	1.05E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.482	2.23E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Bis-2(ethylhexyl) phthalate	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.062mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.006mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 3m	0.2	1.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	8.38E-03	3.45E-23	2.14E-24	3.57E-23	2.21E-24	3.96E-23	2.45E-24
	0.4	1.05E-01	2.86E-08	1.77E-09	3.06E-08	1.90E-09	4.39E-08	2.72E-09
	0.482	2.23E+00	1.84E-03	1.14E-04	2.42E-03	1.50E-04	9.16E-03	5.68E-04

Bis-2(ethylhexyl) phthalate	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.062mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.006mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 5m	0.2	1.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	8.38E-03	4.56E-31	2.83E-32	4.56E-31	2.83E-32	5.66E-31	3.51E-32
	0.4	1.05E-01	1.11E-11	6.89E-13	1.31E-11	8.10E-13	2.58E-11	1.60E-12
	0.482	2.23E+00	5.79E-05	3.59E-06	8.90E-05	5.52E-06	8.58E-04	5.32E-05

Bis-2(ethylhexyl) phthalate	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.062mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.006mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 15m	0.2	1.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	8.38E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.4	1.05E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.482	2.23E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

SANDY LOAM			Time: 1d		Time: 21d		Time: 150d	
Chlordane	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.002mg/L	0.1	8.97E-05	4.14E-26	4.14E-28	4.14E-26	4.14E-28	4.14E-26	4.14E-28
Depth: 3m	0.2	2.14E-02	5.59E-04	5.59E-06	5.79E-04	5.79E-06	5.79E-04	5.79E-06
	0.3	4.16E-01	1.12E-02	1.12E-04	1.16E-02	1.16E-04	1.28E-02	1.28E-04
	0.387	1.55E+01	6.45E-02	6.45E-04	7.77E-02	7.77E-04	1.96E-01	1.96E-03
Chlordane	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.002mg/L	0.1	8.97E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 5m	0.2	2.14E-02	3.25E-06	3.25E-08	3.25E-06	3.25E-08	3.41E-06	3.41E-08
	0.3	4.16E-01	3.00E-04	3.00E-06	3.14E-04	3.14E-06	3.63E-04	3.63E-06
	0.387	1.55E+01	1.84E-02	1.84E-04	2.24E-02	2.24E-04	6.39E-02	6.39E-04
Chlordane	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.002mg/L	0.1	8.97E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 15m	0.2	2.14E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	4.16E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.387	1.55E+01	3.66E-04	3.66E-06	4.25E-04	4.25E-06	1.27E-03	1.27E-05

Methylene Chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	8.97E-05	2.52E-29	3.78E-31	2.61E-29	3.91E-31	3.31E-29	4.96E-31
Depth: 3m	0.2	2.14E-02	3.46E-04	5.19E-06	6.05E-04	9.07E-06	6.36E-03	9.53E-05
	0.3	4.16E-01	2.37E-02	3.55E-04	1.03E-01	1.54E-03	3.54E-01	5.31E-03
	0.387	1.55E+01	2.55E-01	3.83E-03	8.51E-01	1.28E-02	8.64E-01	1.30E-02

Methylene Chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	8.97E-05	5.24E-39	7.86E-41	5.46E-39	8.19E-41	8.73E-39	1.31E-40
Depth: 5m	0.2	2.14E-02	4.15E-06	6.23E-08	1.12E-05	1.67E-07	8.75E-04	1.31E-05
	0.3	4.16E-01	4.37E-03	6.56E-05	3.56E-02	5.35E-04	2.58E-01	3.87E-03
	0.387	1.55E+01	2.11E-01	3.17E-03	7.80E-01	1.17E-02	8.19E-01	1.23E-02

Methylene Chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	8.97E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 15m	0.2	2.14E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.63E-09	2.44E-11
	0.3	4.16E-01	1.29E-05	1.94E-07	4.11E-04	6.16E-06	9.24E-02	1.39E-03
	0.387	1.55E+01	1.41E-01	2.12E-03	5.22E-01	7.83E-03	6.86E-01	1.03E-02

Pentachlorophenol	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.115mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.001mg/L	0.1	8.97E-05	1.25E-69	1.44E-70	1.25E-69	1.44E-70	1.25E-69	1.44E-70
Depth: 3m	0.2	2.14E-02	8.39E-07	9.64E-08	8.68E-07	9.98E-08	8.99E-07	1.03E-07
	0.3	4.16E-01	2.56E-03	2.94E-04	2.64E-03	3.04E-04	3.43E-03	3.94E-04
	0.387	1.55E+01	5.09E-02	5.85E-03	6.29E-02	7.23E-03	2.02E-01	2.33E-02

Pentachlorophenol	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.115mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.001mg/L	0.1	8.97E-05	4.35E-91	5.00E-92	4.35E-91	5.00E-92	4.56E-91	5.25E-92
Depth: 5m	0.2	2.14E-02	7.34E-10	8.44E-11	7.34E-10	8.44E-11	8.09E-10	9.30E-11
	0.3	4.16E-01	4.44E-05	5.10E-06	4.66E-05	5.36E-06	7.50E-05	8.62E-06
	0.387	1.55E+01	1.30E-02	1.50E-03	1.70E-02	1.96E-03	7.77E-02	8.94E-03

Pentachlorophenol	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.115mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.001mg/L	0.1	8.97E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 15m	0.2	2.14E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	4.16E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.387	1.55E+01	1.82E-04	2.09E-05	2.59E-04	2.98E-05	1.94E-03	2.23E-04

Chrysene	Soil Moisture	Unsat.HC		Ratio	Concentration		Ratio	Concentration		Ratio	Concentration
Concentration: 0.01mg/L	0.04	9.62E-15		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Standard: 0.0092mg/L	0.1	8.97E-05		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Depth: 3m	0.2	2.14E-02		8.70E-16	8.70E-18		8.70E-16	8.70E-18		8.70E-16	8.70E-18
	0.3	4.16E-01		1.76E-05	1.76E-07		1.76E-05	1.76E-07		1.82E-05	1.82E-07
	0.387	1.55E+01		7.75E-03	7.75E-05		7.75E-03	7.75E-05		8.02E-03	8.02E-05

Chrysene	Soil Moisture	Unsat.HC		Ratio	Concentration		Ratio	Concentration		Ratio	Concentration
Concentration: 0.01mg/L	0.04	9.62E-15		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Standard: 0.0092mg/L	0.1	8.97E-05		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Depth: 5m	0.2	2.14E-02		1.48E-21	1.48E-23		1.48E-21	1.48E-23		1.48E-21	1.48E-23
	0.3	4.16E-01		3.31E-08	3.31E-10		3.31E-08	3.31E-10		3.31E-08	3.31E-10
	0.387	1.55E+01		1.60E-04	1.60E-06		1.60E-04	1.60E-06		1.68E-04	1.68E-06

Chrysene	Soil Moisture	Unsat.HC		Ratio	Concentration		Ratio	Concentration		Ratio	Concentration
Concentration: 0.01mg/L	0.04	9.62E-15		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Standard: 0.0092mg/L	0.1	8.97E-05		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Depth: 15m	0.2	2.14E-02		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
	0.3	4.16E-01		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
	0.387	1.55E+01		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00

Bis-2(ethylhexyl) phthalate	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.062mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.006mg/L	0.1	8.97E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 3 m	0.2	2.14E-02	1.25E-16	7.73E-18	1.29E-16	8.00E-18	1.43E-16	8.86E-18
	0.3	4.16E-01	1.44E-05	8.95E-07	1.54E-05	9.56E-07	2.56E-05	1.59E-06
	0.387	1.55E+01	1.91E-02	1.19E-03	2.78E-02	1.72E-03	1.50E-01	9.30E-03

Bis-2(ethylhexyl) phthalate	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.062mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.006mg/L	0.1	8.97E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 5m	0.2	2.14E-02	1.4299E-22	8.87E-24	1.43E-22	8.87E-24	1.76E-22	1.09E-23
	0.3	4.16E-01	4.79E-08	2.97E-09	5.55E-08	3.44E-09	1.41E-07	8.73E-09
	0.387	1.55E+01	3.20E-03	1.99E-04	5.37E-03	3.33E-04	6.12E-02	3.79E-03

Bis-2(ethylhexyl) phthalate	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.062mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.006mg/L	0.1	8.97E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 15m	0.2	2.14E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	4.16E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.387	1.55E+01	7.23E-06	4.48E-07	1.55E-05	9.61E-07	1.01E-03	6.28E-05

CLAY LOAM			Time: 1d		Time: 21d		Time: 150d	
Chlordane	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.08	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.002mg/L	0.1	1.64E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 3m	0.2	6.11E-04	6.87E-11	6.87E-13	6.87E-11	6.87E-13	7.12E-11	7.12E-13
	0.3	2.57E-02	9.88E-04	9.88E-06	9.88E-04	9.88E-06	1.02E-03	1.02E-05
	0.4	4.10E-01	1.22E-02	1.22E-04	1.22E-02	1.22E-04	1.44E-02	1.44E-04
	0.442	5.00E+00	4.01E-02	4.01E-04	4.38E-02	4.38E-04	7.54E-02	7.54E-04
Chlordane	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.08	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.002mg/L	0.1	1.64E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 5m	0.2	6.11E-04	3.13E-15	3.13E-17	3.13E-15	3.13E-17	3.13E-15	3.13E-17
	0.3	2.57E-02	6.81E-06	6.81E-08	6.81E-06	6.81E-08	7.14E-06	7.14E-08
	0.4	4.10E-01	3.54E-04	3.54E-06	3.54E-04	3.54E-06	4.47E-04	4.47E-06
	0.442	5.00E+00	5.94E-03	5.94E-05	6.67E-03	6.67E-05	1.34E-02	1.34E-04
Chlordane	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.08	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.002mg/L	0.1	1.64E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 15m	0.2	6.11E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	2.57E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.4	4.10E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.442	5.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.47E-06	6.47E-08

Methylene Chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.08	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	1.64E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 3m	0.2	6.11E-04	3.04E-13	4.56E-15	3.37E-13	5.05E-15	7.24E-13	1.09E-14
	0.3	2.57E-02	4.29E-04	6.44E-06	8.68E-04	1.30E-05	1.07E-02	1.61E-04
	0.4	4.10E-01	2.20E-02	3.30E-04	1.06E-01	1.60E-03	3.38E-01	5.06E-03
	0.442	5.00E+00	1.49E-01	2.23E-03	6.84E-01	1.03E-02	7.50E-01	1.12E-02
Methylene Chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.08	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	1.64E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 5m	0.2	6.11E-04	3.40E-18	5.09E-20	4.38E-18	6.56E-20	1.88E-17	2.82E-19
	0.3	2.57E-02	5.74E-06	8.61E-08	1.98E-05	2.97E-07	5.99E-04	8.99E-06
	0.4	4.10E-01	3.83E-03	5.75E-05	3.66E-02	5.50E-04	2.43E-01	3.64E-03
	0.442	5.00E+00	9.82E-02	1.47E-03	4.05E-01	6.08E-03	6.81E-01	1.02E-02
Methylene Chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.08	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	1.64E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 15m	0.2	6.11E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	2.57E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.42E-08	9.62E-10
	0.4	4.10E-01	7.90E-06	1.18E-07	3.69E-04	5.54E-06	8.31E-02	1.25E-03
	0.442	5.00E+00	3.91E-02	5.86E-04	2.68E-01	4.02E-03	4.97E-01	7.46E-03

Pentachlorophenol	Soil Moisture	Unsat.HC		Ratio	Concentration		Ratio	Concentration		Ratio	Concentration
Concentration: 0.115mg/L	0.08	1.92E-16		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Standard: 0.001mg/L	0.1	1.64E-08		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Depth: 3m	0.2	6.11E-04		2.27E-26	2.61E-27		2.27E-26	2.61E-27		2.35E-26	2.70E-27
	0.3	2.57E-02		3.98E-06	4.58E-07		3.98E-06	4.58E-07		4.41E-06	5.07E-07
	0.4	4.10E-01		3.05E-03	3.51E-04		3.16E-03	3.63E-04		4.49E-03	5.16E-04
	0.442	5.00E+00		2.70E-02	3.11E-03		3.13E-02	3.60E-03		7.85E-02	9.03E-03

Pentachlorophenol	Soil Moisture	Unsat.HC		Ratio	Concentration		Ratio	Concentration		Ratio	Concentration
Concentration: 0.115mg/L	0.08	1.92E-16		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Standard: 0.001mg/L	0.1	1.64E-08		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Depth: 5m	0.2	6.11E-04		3.20E-35	3.68E-36		3.20E-35	3.68E-36		3.35E-35	3.86E-36
	0.3	2.57E-02		5.51E-09	6.34E-10		5.51E-09	6.34E-10		6.40E-09	7.36E-10
	0.4	4.10E-01		5.62E-05	6.46E-06		6.18E-05	7.11E-06		1.14E-04	1.31E-05
	0.442	5.00E+00		3.43E-03	3.95E-04		4.33E-03	4.98E-04		1.67E-02	1.92E-03

Pentachlorophenol	Soil Moisture	Unsat.HC		Ratio	Concentration		Ratio	Concentration		Ratio	Concentration
Concentration: 0.115mg/L	0.08	1.92E-16		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Standard: 0.001mg/L	0.1	1.64E-08		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Depth: 15m	0.2	6.11E-04		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
	0.3	2.57E-02		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
	0.4	4.10E-01		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
	0.442	5.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00		1.20E-05	1.38E-06

Chrysene	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.08	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.0092mg/L	0.1	1.64E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 3m	0.2	6.11E-04	2.10E-75	2.10E-77	2.10E-75	2.10E-77	2.10E-75	2.10E-77
	0.3	2.57E-02	1.01E-13	1.01E-15	1.01E-13	1.01E-15	1.01E-13	1.01E-15
	0.4	4.10E-01	2.91E-05	2.91E-07	2.91E-05	2.91E-07	2.91E-05	2.91E-07
	0.442	5.00E+00	3.31E-03	3.31E-05	3.31E-03	3.31E-05	3.42E-03	3.42E-05

Chrysene	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.08	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.0092mg/L	0.1	1.64E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 5m	0.2	6.11E-04	1.53E-98	1.53E-100	1.53E-98	1.53E-100	1.53E-98	1.53E-100
	0.3	2.57E-02	6.84E-19	6.84E-21	6.84E-19	6.84E-21	6.84E-19	6.84E-21
	0.4	4.10E-01	6.06E-08	6.06E-10	6.06E-08	6.06E-10	6.06E-08	6.06E-10
	0.442	5.00E+00	4.06E-05	4.06E-07	4.26E-05	4.26E-07	4.26E-05	4.26E-07

Chrysene	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.01mg/L	0.08	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.0092mg/L	0.1	1.64E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 15m	0.2	6.11E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	2.57E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.4	4.10E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.442	5.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Bis-2(ethylhexyl) phthalate	Soil Moisture	Unsat.HC		Ratio	Concentration		Ratio	Concentration		Ratio	Concentration
Concentration: 0.062mg/L	0.08	1.92E-16		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Standard: 0.006mg/L	0.1	1.64E-08		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Depth: 3m	0.2	6.11E-04		3.03E-80	1.88E-81		3.03E-80	1.88E-81		3.14E-80	1.95E-81
	0.3	2.57E-02		1.83E-14	1.13E-15		1.89E-14	1.17E-15		2.24E-14	1.39E-15
	0.4	4.10E-01		2.33E-05	1.44E-06		2.66E-05	1.65E-06		5.09E-05	3.16E-06
	0.442	5.00E+00		6.06E-03	3.76E-04		8.36E-03	5.18E-04		3.97E-02	2.46E-03
Bis-2(ethylhexyl) phthalate	Soil Moisture	Unsat.HC		Ratio	Concentration		Ratio	Concentration		Ratio	Concentration
Concentration: 0.062mg/L	0.08	1.92E-16		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Standard: 0.006mg/L	0.1	1.64E-08		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Depth: 5m	0.2	6.11E-04		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
	0.3	2.57E-02		9.42E-20	5.84E-21		9.90E-20	6.14E-21		1.36E-19	8.41E-21
	0.4	4.10E-01		9.76E-08	6.05E-09		1.19E-07	7.38E-09		3.89E-07	2.41E-08
	0.442	5.00E+00		4.21E-04	2.61E-05		6.78E-04	4.20E-05		8.37E-03	5.19E-04
Bis-2(ethylhexyl) phthalate	Soil Moisture	Unsat.HC		Ratio	Concentration		Ratio	Concentration		Ratio	Concentration
Concentration: 0.062mg/L	0.08	1.92E-16		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Standard: 0.006mg/L	0.1	1.64E-08		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Depth: 15m	0.2	6.11E-04		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
	0.3	2.57E-02		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
	0.4	4.10E-01		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
	0.442	5.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00		2.64E-06	1.63E-07

APPENDIX G: CONCENTRATIONS OF METHYLENE CHLORIDE IN WATER IN THREE SOIL TYPES

SILTY CLAY LOAM			Time: 1d		Time: 21d		Time: 150d	
Methylene chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.091	4.58E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	2.24E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 20m	0.2	1.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	8.38E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.4	1.05E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.47E-03	2.20E-05
	0.482	2.23E+00	4.28E-03	6.42E-05	5.57E-02	8.35E-04	2.81E-01	4.22E-03

SANDY LOAM			Time: 1d		Time: 21d		Time: 150d	
Methylene chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	8.97E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 20m	0.2	2.14E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	4.16E-01	2.22E-06	3.33E-08	7.83E-05	1.17E-06	6.33E-02	9.50E-04
	0.387	1.55E+01	1.27E-01	1.91E-03	4.97E-01	7.46E-03	6.43E-01	9.64E-03

Methylene chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	8.97E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 30m	0.2	2.14E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	4.16E-01	0.00E+00	0.00E+00	6.58E-06	9.87E-08	3.30E-02	4.95E-04
	0.387	1.55E+01	1.10E-01	1.64E-03	5.39E-01	8.08E-03	5.76E-01	8.64E-03

Methylene chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.04	9.62E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	8.97E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 40m	0.2	2.14E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	4.16E-01	0.00E+00	0.00E+00	1.09E-06	1.63E-08	1.76E-02	2.64E-04
	0.387	1.55E+01	1.40E-01	2.10E-03	2.80E-01	4.21E-03	5.25E-01	7.88E-03
CLAY LOAM			Time: 1d		Time: 21d		Time: 150d	
Methylene chloride	Soil Moisture	Unsat.HC	Ratio	Concentration	Ratio	Concentration	Ratio	Concentration
Concentration: 0.015mg/L	0.08	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	1.64E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 20m	0.2	6.11E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	2.57E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.4	4.10E-01	1.12E-06	1.69E-08	6.32E-05	9.48E-07	5.62E-02	8.43E-04
	0.442	5.00E+00	3.13E-02	4.69E-04	2.01E-01	3.02E-03	4.43E-01	6.64E-03
Methylene chloride	Soil Moisture	Unsat.HC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Concentration: 0.015mg/L	0.08	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	1.64E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Depth: 30m	0.2	6.11E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.3	2.57E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.4	4.10E-01	0.00E+00	0.00E+00	4.51E-06	6.76E-08	2.89E-02	4.34E-04
	0.442	5.00E+00	2.25E-02	3.37E-04	1.26E-01	1.89E-03	3.65E-01	5.47E-03

Methylene chloride	Soil Moisture	Unsat.HC		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Concentration: 0.015mg/L	0.08	1.92E-16		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Standard: 0.005mg/L	0.1	1.64E-08		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
Depth: 40m	0.2	6.11E-04		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
	0.3	2.57E-02		0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00
	0.4	4.10E-01		0.00E+00	0.00E+00		6.68E-07	1.00E-08		1.59E-02	2.39E-04
	0.442	5.00E+00		1.75E-02	2.63E-04		8.86E-02	1.33E-03		3.10E-01	4.65E-03