BUREAU OF RECLAMATION

Evaluating Low Impact Development and Surface Water-Groundwater Interactions in the Los Angeles Basin

Pilot Study
Los Angeles County, California



U.S. Department of the Interior

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Evaluating Low Impact Development and Surface Water-Groundwater Interactions Water Management Operations

Pilot Study
Los Angeles County, California

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Cover Photo: Rosemead Bioswale (Reclamation/Brett Mooney)

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Acronyms and Abbreviations

af	acre-feet (1 af = 43,560 cubic feet = 325,851 gallons)
af/yr	acre-feet per year
BMP	Best Management Practices
CP	Carsel and Parrish
CPT	cone penetrometer test
ERT	Electrical Resistivity Tomography
ft	feet
GI	Green Infrastructure
GWAM	Groundwater Augmentation Model
hr	hour
LA	Los Angeles
LACPW	Los Angeles County Public Works
LBNL	Lawrence Berkeley National Laboratory
LID	Low Impact Development
LSPC	LA County's Load Simulation Program in C++
MWD	The Metropolitan Water District of Southern California
NP	neutron probe
Reclamation	U.S. Bureau of Reclamation
SCCWRP	Southern California Coastal Water Research Project
SCMP	Stormwater Capture Master Plan
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VS2DI	USGS graphical software package for simulating flow and transport
VWC	volumetric water content
WAS	Water Augmentation Study
WMMS	Watershed Management Modeling System
WRD	Water Replenishment District of Southern California

Symbols

≈	almost equal to
Δ	delta (change)
=	equal to
≥	greater than or equal to
≤	less than or equal to
%	percent
~	roughly, about
θ	theta (volumetric water content)

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1. Executive Summary

This Water Management Operations Pilot Study evaluated the effectiveness of Low Impact Development (LID) Best Management Practices (BMPs) in enhancing groundwater recharge within Los Angeles County. The study addressed two primary objectives: (1) collected field data to quantify deep percolation rates beneath various LID types, and (2) developed calibrated infiltration models using computer software to predict recharge performance under site-specific conditions. In particular, the study quantifies deep percolation rates—which represent the movement of water below the root zone—and uses these rates to estimate the potential for groundwater recharge.

To achieve these objectives, three LID sites were monitored using neutron probes to assess infiltration and percolation: Rosemead Bioswale, Headquarters Drywell, and Van Nuys Drywell. The report presents data by borehole location and probe readings. Synthetic storm events were conducted for controlled inflow, with subsurface responses tracked using neutron probes. Numerical models were developed and calibrated using VS2DI software to replicate observed infiltration patterns and wetting fronts. Deep percolation rates representing average steady-state velocities were developed from the calibrated models and yielded the following results for the simulated storm events:

- Rosemead Bioswale: 0.4–0.5 ft/hr.
- Headquarters Drywell: 0.2–0.4 ft/hr.
- Van Nuys Drywell: 8.3 ft/hr.

Results presented herein are based on calibrated numerical models and are subject to the assumptions and limitations described in this report.

2. Introduction

2.1 Objectives

This Water Management Operations Pilot Study evaluates the potential for Low Impact Development (LID) Best Management Practices (BMPs) to contribute to groundwater recharge[1] in Los Angeles County, emphasizing the importance of these practices for long-term water resilience. To support this evaluation, the project pursued two primary objectives:

1. Obtain field data to determine deep percolation rates associated with various LID BMP types.

2. Develop an infiltration modeling tool for determining deep percolation rates associated with various LID BMP types.

Data collection was accomplished by instrumenting three LID BMP sites and monitoring both synthetic and natural storm events. The resulting dataset informed the calibration of infiltration models for each BMP, providing insights into their potential to enhance recharge.

3. Study Background and Context

Groundwater recharge is essential to the long-term reliability of Los Angeles County's water supply. Local aquifers provide large, naturally protected storage that can be replenished during wet periods and withdrawn during dry periods. However, the potential for natural recharge has declined significantly due to extensive urbanization, including the proliferation of impervious surfaces and the construction of channelized waterways that rapidly divert stormwater to the ocean.

Recognizing these challenges, the 2016 Los Angeles (LA) Basin Study (Study) evaluated strategies to enhance stormwater capture for groundwater recharge and emphasized the need for improved stormwater infrastructure to support long-term water resilience under variable precipitation conditions. The Study identified decentralized infiltration BMPs—including Local Stormwater Capture, Low Impact Development (LID), and Complete Streets—as essential components. It estimated that widespread implementation of these BMPs could increase local water supplies by over 183,000 acre-feet per year (af/yr), including 94,500 af/yr specifically from LID features. These findings illustrate the scale of recharge that distributed LID strategies may provide, largely because the Study assumes broad regional adoption, highly favorable soil and siting conditions, and significant hydrologic performance improvements across large urban areas.

[1]In this report, "deep percolation" refers to the downward movement of water beyond the root zone (typically below 3 feet), while "groundwater recharge" is defined as water that reaches and replenishes the aquifer. Although these terms are sometimes used interchangeably in the literature, this report distinguishes between them as defined in Section 5.1. Where the specific meaning is important, the report uses the terms as defined; otherwise, "deep percolation" is used to describe modeled or measured downward water movement, and "groundwater recharge" is reserved for water that actually reaches the aquifer.

Expanding distributed recharge through Low Impact Development (LID) practices therefore presents an opportunity to enhance a critical resource. When properly sited over permeable soils and accessible aquifers, LID features can reduce stormwater runoff, increase infiltration, and help restore a more sustainable balance between groundwater replenishment and withdrawal. Quantifying how much recharge LID practices can realistically contribute, and under what site conditions, is essential for understanding their role in future water-supply planning. This study addresses that need through field monitoring and calibrated VS2DI infiltration models that estimate deep percolation beneath representative LID types across Los Angeles County.

3.1 Watersheds and Groundwater Basins

There are seven major watersheds within the Los Angeles Basin: the Los Angeles River, San Gabriel River, South Santa Monica Bay, North Santa Monica Bay, Ballona Creek, Malibu Creek, and the Dominguez Channel/Los Angeles Harbor Watersheds. Together, these watersheds cover approximately 2,040 square miles of LA County.

There are twenty-three groundwater basins within Los Angeles County (County of Los Angeles, 2024). Figure 1 shows several major groundwater basins in the study area, including Central, Main San Gabriel, Raymond, and San Fernando.



Figure 1.—Major groundwater basins in the study area.

3.2 Water Supply and Economic Importance

Los Angeles County's water demand is the highest in California, due to its population, agriculture, and industry. Within the Los Angeles Basin, the region primarily relies on two water sources: imported water which constitutes 57% of supply, and groundwater which accounts for 35%. Stormwater capture, considered part of groundwater supply, provides about 11%.

Figure 2 shows the 2014 Los Angeles Basin water supply portfolio from the Greater Los Angeles County Integrated Regional Water Management Plan (GLAC IRWMP, 2014), with a nested chart highlighting the significant contribution of groundwater. The water supply portfolio may have changed in subsequent years.

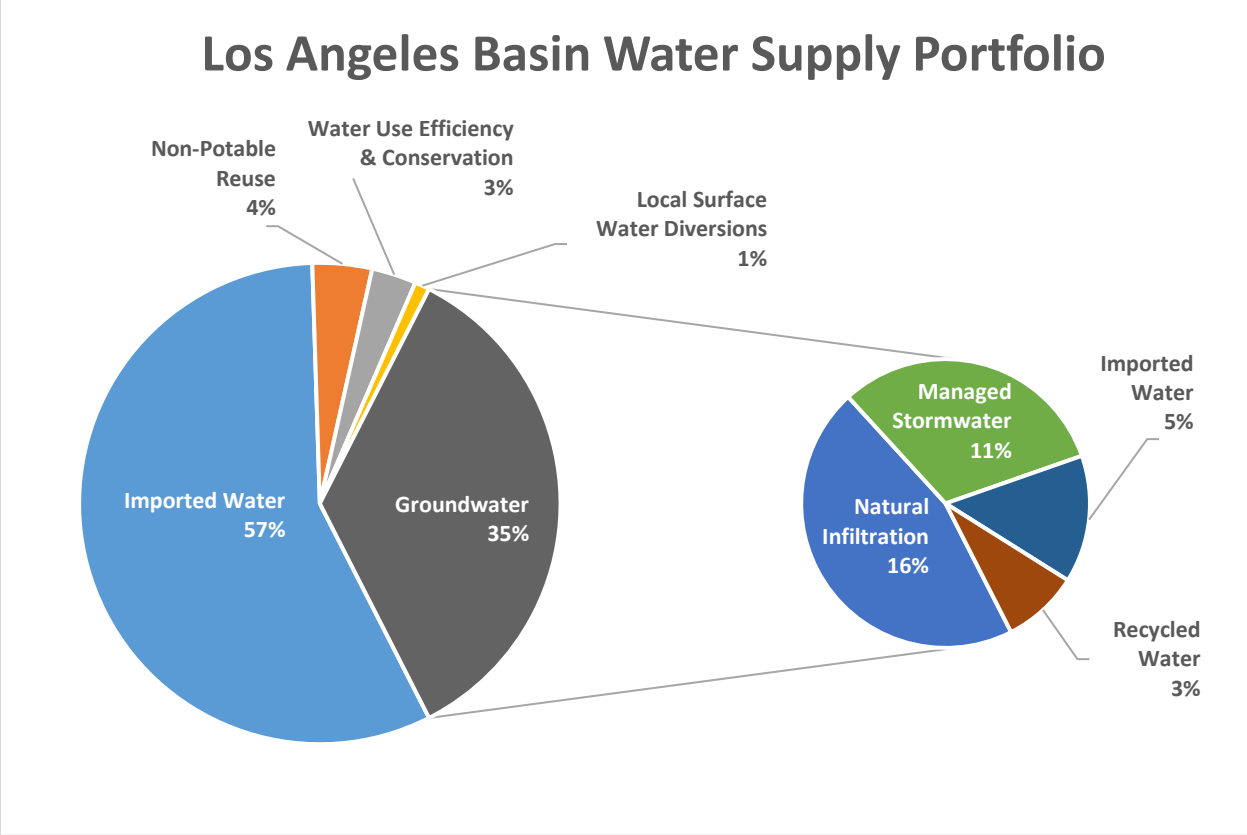

Figure 2.—Los Angeles Basin water supply portfolio, GLAC IRWMP 2014 data.

The main sources of imported water are Northern California (State Water Project), the Colorado River Basin, and the LA Aqueduct (LACPW, 2026). Water retailers acquire these supplies from local contractors or regional wholesale agencies, such as the Metropolitan Water District of Southern California (MWD). In fiscal year 2017-2018, the LA Basin portion of MWD's service area used 1.55 million acre-feet (af) of water, with demand projected to increase to about 1.7 million af/yr in the coming decades. However, the reliability of these imported water sources is increasingly uncertain due to environmental, social, and political factors. Recurring droughts in Northern California and

the Colorado River Basin, court rulings regarding endangered species in the Sacramento-San Joaquin Delta, changing demographics, climate-related impacts to water resources, and competing water uses all pose long-term risks to the stability of imported water supplies (Reclamation, 2016).

Aquifer recharge is essential for maintaining a reliable water supply in the LA Basin, where local groundwater accounts for approximately one-third of the total water supply. A lack of confidence in a resilient water supply in LA County could lead to significant economic consequences. Long-term economic and business strategies depend heavily on the stability of essential services and resources, particularly water supply.

3.3 Overview of Stormwater Management Strategies: BMPs and LIDs

Best Management Practices (BMPs) are techniques used to manage stormwater runoff and reduce pollution. These practices can be structural—meaning they involve physical, engineered structures—or non-structural and aim to lessen the effects of land development on water quality and quantity. Examples of BMPs include erosion control, vegetative swales, detention basins, and oil-water separators, among others. They can be applied at various stages of land development and can complement Low Impact Development (LID) strategies.

Low Impact Development (LID) practices are decentralized stormwater management approaches designed to capture, infiltrate, and treat runoff as close to its source as possible. These strategies aim to mimic natural hydrologic processes by increasing surface area available for infiltration, enhancing infiltration pathways, and reducing runoff. When integrated into the urban landscape, LID can provide meaningful contributions to groundwater recharge, water quality improvement, and local flood mitigation (EPA, 2009a).

3.4 Stormwater Capture and Aquifer Recharge Benefits

The sources of aquifer recharge in the LA Basin include natural infiltration, recycled water, imported water, and managed stormwater. Low Impact Development (LID) practices can enhance managed stormwater and aquifer recharge in areas with high infiltration rates (greater than 0.3 inches per hour) located above unconfined aquifers (LACPW, 2014). Figure 3 shows a map of the Los Angeles Basin, depicting BMPs and their corresponding infiltration capabilities, classified as high, medium, or low (Geosyntec Consultants, 2024).

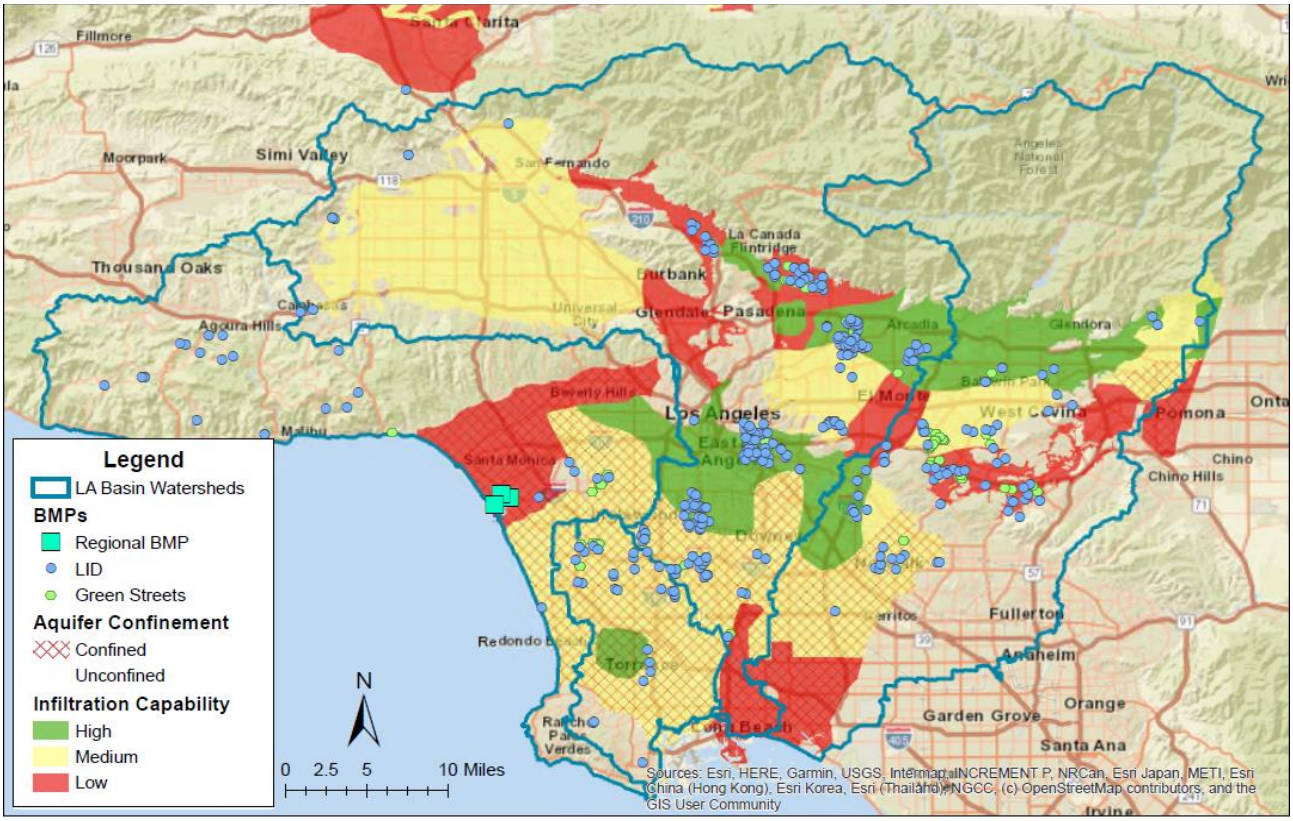

Figure 3.—BMP locations & infiltration capabilities in the LA Basin.

The City of Los Angeles Department of Water and Power (LADWP) Stormwater Capture Master Plan (SCMP) highlights two primary benefits of stormwater capture (LADWP, 2015):

- cost reduction associated with purchasing less imported water, and
- improved water supply reliability.

The SCMP estimated the value of captured stormwater for aquifer recharge using the Metropolitan Water District (MWD) Tier 1 untreated water rates, which range from $850 to $1,000 per acre-foot. The actual cost varies based on whether the stormwater project qualifies for the MWD Local Resource Program subsidy. Additionally, the SCMP suggests conducting further analysis on the value of stormwater capture.

Beyond direct water-supply benefits, stormwater capture projects and LID strategies also provide additional value. The Water Augmentation Study (WAS), for the Los Angeles area, found that the total cost of decentralized stormwater management projects can generate total benefits that are comparable in value to the water supply they produce. Specifically, the WAS estimated that groundwater stored through these decentralized projects—particularly water available for use during dry years—has an economic value ranging from about $757 per acre-foot to $943 per acre-foot (Chesnutt et al., 2008; Cutter, 2007).

3.5 Technical Feasibility and Applicable Ordinances

City ordinances, interagency partnerships, and major development or redevelopment activities all support the widespread implementation of LID practices across the region. Under the MS4 Permit, every city within Los Angeles County—as well as the County itself—is required to adopt and implement a Low Impact Development (LID) ordinance. For example, the City of Los Angeles has enacted an LID Ordinance that requires the use of BMPs on private properties where feasible, and its effectiveness was evaluated in the LA Sustainable Water Project: Los Angeles City-Wide Overview study (see Section A.1.4). Similarly, Los Angeles County has its own LID Ordinance mandating the incorporation of LID measures in new developments and significant redevelopments (Los Angeles & San Gabriel Rivers Watershed Council, 2010).

4. LID Strategies and Implementation Considerations

4.1 Overview of LID and BMP Strategies

LID practices encompass both non-structural and structural stormwater Best Management Practices (BMPs):

Non-structural approaches focus on preserving natural hydrology through minimizing site disturbance, maintaining drainage patterns, reducing impervious surfaces, using native vegetation, and limiting turf grass. Structural BMPs—including bioswales, bioretention basins, infiltration trenches, drywells, and permeable pavement—provide engineered solutions that enhance storage and infiltration when positioned at or near the runoff source.

Together, these practices slow, filter, store, or infiltrate stormwater in a distributed manner across the watershed.

4.2 Benefits of LID

LID implementation can provide a wide range of hydrologic and environmental benefits. By reducing runoff volumes and peak flows, LID features slow and disperse stormwater, allowing more water to infiltrate into the ground and contribute to localized groundwater recharge. As stormwater passes through vegetation and soil, it also experiences natural filtration that improves water quality. These distributed systems enhance resilience under variable climate conditions by providing small-scale storage across the landscape, which reduces pressure on centralized drainage and water-supply infrastructure. In many cases, the additional recharge and reduced runoff can also yield economic benefits, such as lowering the need for imported water or reducing treatment costs. These benefits are most effectively achieved when LID features are placed in areas with suitable soils, adequate depth to groundwater, and appropriate drainage characteristics that support infiltration.

4.3 Limitations and Implementation Challenges

The Los Angeles County Public Works (LACPW) LID Design Standards Manual identifies several conditions under which LID infiltration may be considered technically infeasible. These include sites with low infiltration rates (less than 0.3 inches per hour), shallow groundwater (within 10 feet of the surface), proximity to drinking-water wells (within 100 feet), contaminated or previously polluted sites, and locations where infiltration poses geotechnical risks such as slope instability, static or seismic settlement, surcharge on nearby structures, expansive soils, or impacts to adjacent properties (LACPW, 2014). Because infiltration affects groundwater basins, projects may also require coordination with regulatory agencies.

Widespread LID implementation is further constrained by basin-scale factors, including the need for broad deployment to influence regional hydrology, limited site suitability due to soil or groundwater conditions, groundwater-management complexities (such as water rights and mounding), permitting and regulatory requirements, ongoing maintenance needs, and reliance on property-owner participation for adoption on private parcels.

5. Groundwater Recharge Concepts and Predictors

5.1 Recharge Concepts and Definitions

Groundwater recharge, as defined in this study, is the downward movement of water to the water table, thereby raising the water table and increasing aquifer storage. Recharge is often expressed as a volumetric flow rate (Healy, 2010). Although infiltration refers to the entry of water into the subsurface, not all infiltrated water becomes recharge. Some water is lost to evapotranspiration or stored temporarily within the vadose zone (Healy, 2010). Soil properties, root zone uptake, and depth to groundwater all strongly influence whether infiltrated water ultimately reaches the water table (Bethune, 2004). Direct field measurement of recharge is challenging, and only a limited number of studies perform side-by-side comparisons of modeled recharge and small-scale field measurements (Bond, 1998; Döll & Fiedler, 2008). In regional Low Impact Development studies—including those cited in Appendix A1 and A2—recharge is commonly defined as water that moves beyond the upper soil layers. Because infiltration processes vary with depth, it is important to distinguish between several related terms:

Shallow Percolation
The downward movement of water through the upper soil layers (unsaturated or vadose zone) that infiltrates below the ground surface but does not reach the aquifer. For this study, shallow percolation occurs within the top 3.0 feet of soil (Scanlon et al., 2002).

Deep Percolation
The downward movement of water beyond the 3.0-foot depth threshold, through lower soil layers unaffected by evapotranspiration, a portion of which eventually reaches the aquifer.

Groundwater (Aquifer) Recharge:
Water that percolates deeply enough to replenish a usable and managed groundwater aquifer, excluding water originating from adjacent groundwater systems.

Recharge can occur through two primary pathways:

- Diffuse recharge, which results from widespread, low-intensity infiltration across the landscape, is a key process in semi-arid regions (Döll & Flörke, 2005); or

- Focused recharge, which occurs through concentrated flow zones such as stream channels, retention basins, ephemeral lakes, fractures in bedrock areas, or engineered infiltration systems.

In arid regions such as Los Angeles, engineered focused recharge often dominates due to limited natural infiltration opportunities and episodic stormwater availability (Healy, 2010). Bioswales, drywells, and bioretention systems are examples of LID that are engineered specifically to enhance on-site infiltration:

- **Bioswale -** A vegetated channel that captures and treats stormwater. Vegetation, sedimentation, and soil adsorption processes slow, filter, and infiltrate stormwater.

- **Drywell -** A gravity-fed, aggregate-filled boring with perforated casing that bypasses low-permeability surface soils and conveys stormwater to more permeable layers at depth.

- **Bioretention -** A subsurface chamber or gallery with perforated elements that provide temporary storage and promote infiltration into underlying native soils.

This study evaluates the extent to which these LID BMPs promote deep percolation and groundwater recharge in conditions representative of Los Angeles County.

5.2 Factors Influencing Groundwater Recharge

Groundwater recharge is controlled by a combination of climatic, soil, and landscape factors. On a global scale, meteorological conditions and vegetation exert the strongest influence (Mohan et al., 2018; Döll & Flörke, 2005). In arid regions such as Southern California, recharge depends largely on the availability of surface water generated by precipitation patterns, evapotranspiration rates, and geomorphic features (Scanlon et al., 2012; Döll & Flörke, 2005). Numerous studies confirm these relationships; for example, mean annual precipitation alone accounts for roughly 80% of the variation in recharge across the southwestern United States (Keese et al., 2005). Other factors—including the frequency of rainy days, vegetation type and rooting depth, land use and land cover, and local climate variability—can substantially modify recharge rates, and their influence varies widely from one location to another (Döll & Flörke, 2005).

Soil properties also play a critical role. Soils with low clay content, high infiltration capacity (greater than 0.3 inches per hour), elevated organic matter, and strong sorption characteristics are generally most favorable for groundwater recharge (LACPW, 2014). For infiltration-based LID BMPs in Los Angeles County, the specific type of LID and its vertical and lateral proximity to groundwater aquifers are additional predictors of performance, as they govern whether infiltrated stormwater has a reasonable likelihood to reach the aquifer.

6. LID Site Selection and Descriptions

Site locations to study LID functionality were carefully selected based on several criteria such as LID type, infiltration capacity, storage volume, and drainage area. The following sections identify specific details of each selected site.

6.1 Site Locations and Facts

Table 1 details the LID types and instrumentation used in this Study. Neutron probe names correspond to their respective boreholes.

Table 1.—LID locations and facts

LID Name	Location	Facts	Instrumentation
Rosemead Bioswale	West side of Rosemead Blvd. near intersection with San Pasqual St. Pasadena, CA. 34°08'15.4"N, 118°04'24.5"W	Watershed: Los Angeles River Groundwater Basin: Raymond Basin 1 Component: Bioswale.	Two boreholes were drilled in the bioswale as shown in Figure 5, and neutron probes were inserted.
Headquarters Drywell	Parking lot south and west of Los Angeles County Public Works building. Alhambra, CA. 34°05'03.3"N, 118°09'2.3"W	Watershed: Los Angeles River Groundwater Basin: Main San Gabriel 4 Components: Primary chamber, drywell chamber, drywell, and underground detention chamber[1].	Three boreholes were drilled near the drywell as shown in Figure 8, and neutron probes were inserted.
Van Nuys Green Streets Project (Bioretention & Drywell)	Just northwest of the intersection of El Dorado Ave and Mercer St. Pacoima, CA. 34°15'59.6"N, 118°25'31.9"W	Watershed: Los Angeles River Groundwater Basin: San Fernando Basin 2 Components: Bioretention planting and drywell.	Two boreholes were drilled near the drywell as shown in Figure 11, and neutron probes were inserted.

[1] The underground detention chamber was not included in the analysis because, during the synthetic storm event, water was intentionally prevented from entering this chamber.

6.2 Rosemead Bioswale Details

Stormwater runoff from Rosemead Blvd. enters the bioswale through curb openings and a sloped apron, which directs water into a shallow vegetated area. Here, plants and mulch slow the flow, reduce erosion, and trap solids. A permeable soil layer beneath the bioswale further improves infiltration, allowing water to percolate into the soil.

6.2.1 Hydrogeological Setting

The Rosemead Bioswale is in the Raymond Groundwater Basin, underlain by a vadose zone approximately 217 feet thick above the water table. The upper 3 feet consist of loamy sand with high infiltration capacity, underlain by sandy loam and sand layers. Field borings and lab analyses confirm predominantly sandy textures with minor silt and clay, supporting rapid infiltration. The site is not affected by shallow groundwater or known contamination, and the stratigraphy provides a direct

pathway for infiltrated water to reach the underlying aquifer. Instrumentation includes two boreholes with neutron probes for monitoring soil moisture changes during storm events.



Figure 4.—Rosemead Bioswale.

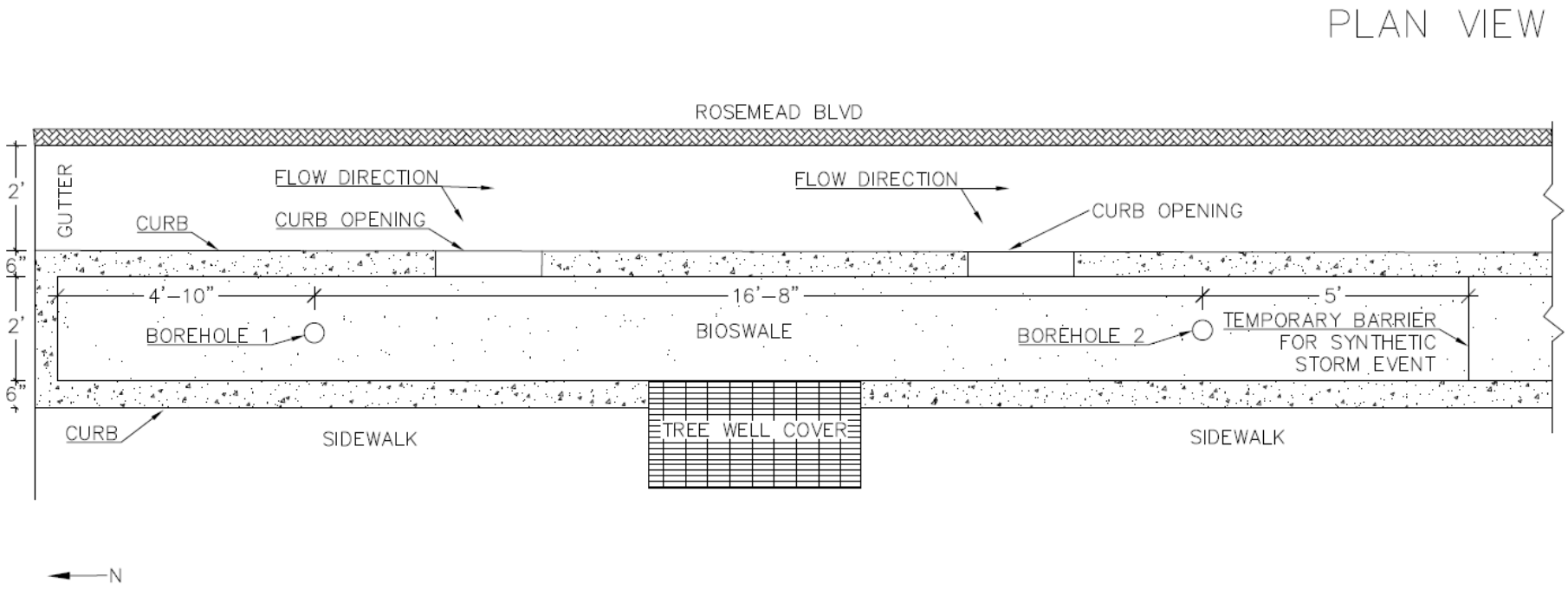

Figure 5.—Rosemead Bioswale plan view.

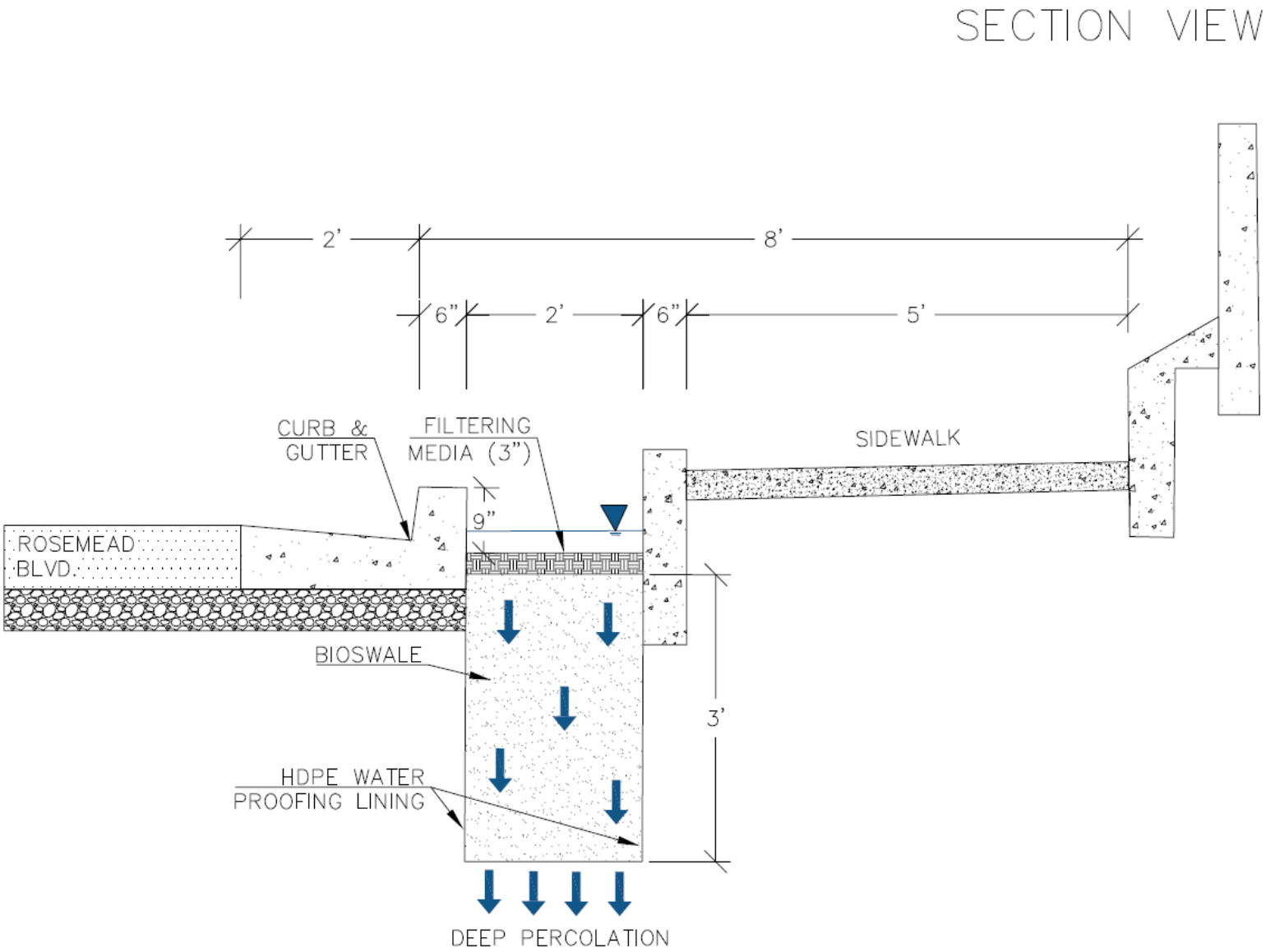

Figure 6.—Rosemead Bioswale section view.

6.3 Headquarters Drywell Details

The Headquarters Drywell consists of four components: 1) primary chamber, 2) drywell chamber, 3) drywell, and 4) underground detention chamber. The system operates as follows.

Stormwater first enters the primary chamber, where it infiltrates into the ground. If the chamber's infiltration capacity is exceeded, water rises up to 10 feet above the chamber bottom and flows into the drywell chamber for further infiltration. When the drywell chamber also reaches its capacity, water rises again to 10 feet above the chamber bottom, enters the drainage pipe, and flows into the drywell to a depth of approximately 65 feet. If all chambers are at maximum capacity, excess water is directed to the underground detention chamber, which was not evaluated in this analysis. Figure 8 provides a plan view of the Headquarters infiltration system, while Figure 9 shows its elevation view.



Figure 7—Headquarters Drywell during construction.

6.3.1 Hydrogeological Setting

The Headquarters Drywell is in the Main San Gabriel Groundwater Basin, with a vadose zone approximately 308 feet thick above the water table. The subsurface profile consists of sandy loam and sandy clay loam in the upper 8.5 feet, underlain by alternating layers of silt loam, loam, and sand to depths exceeding 70 feet. Laboratory and field analyses confirm a mix of sandy and silty textures, with hydraulic conductivities ranging from moderate to low, reflecting some restrictive layers. The site is not affected by shallow groundwater or known contamination, and stratigraphy allows for

vertical migration of infiltrated water, although some layers may slow percolation. Three boreholes with neutron probes were installed to monitor soil moisture changes and infiltration dynamics during storm events.

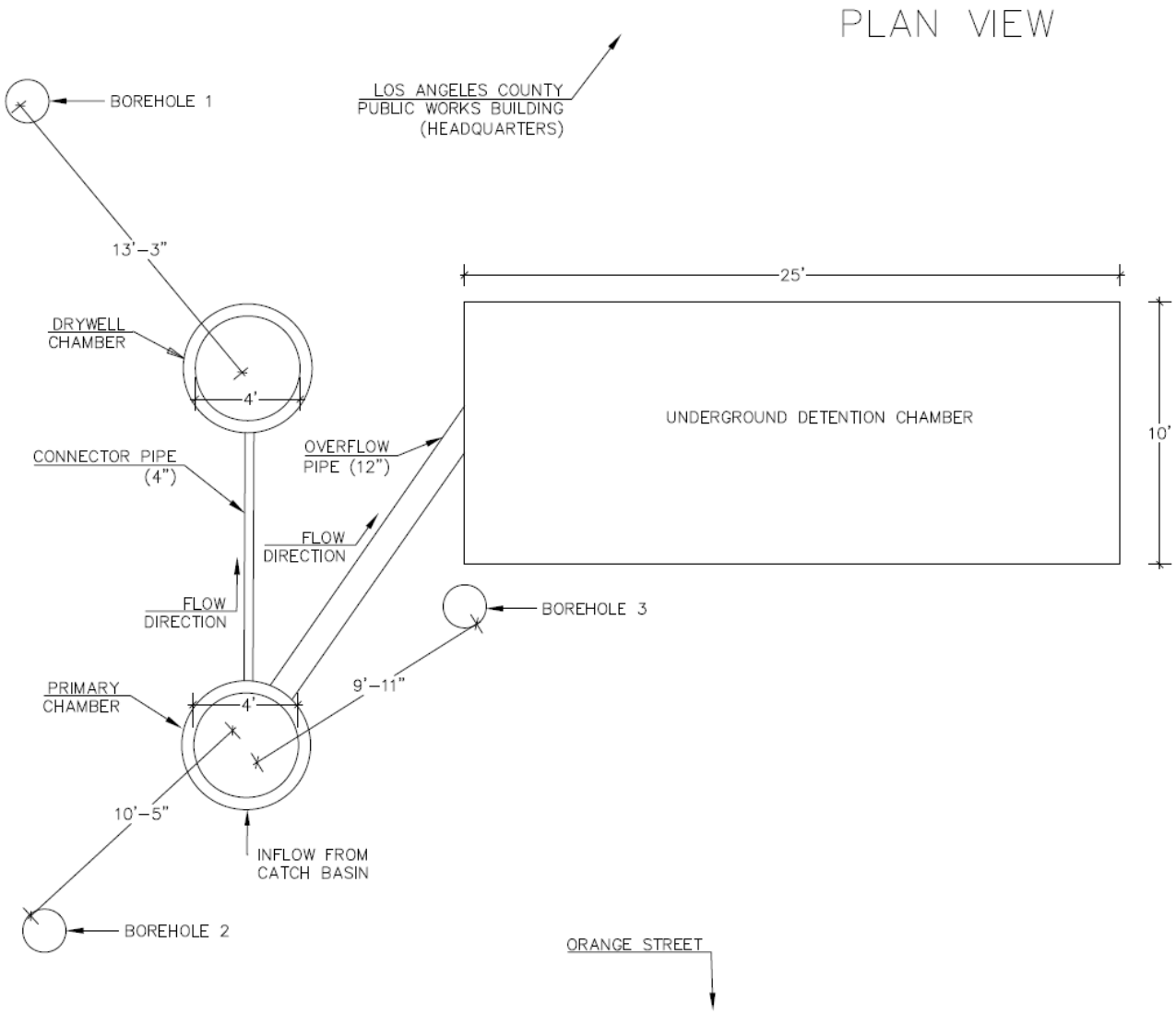

Figure 8.—Headquarters Drywell plan view.

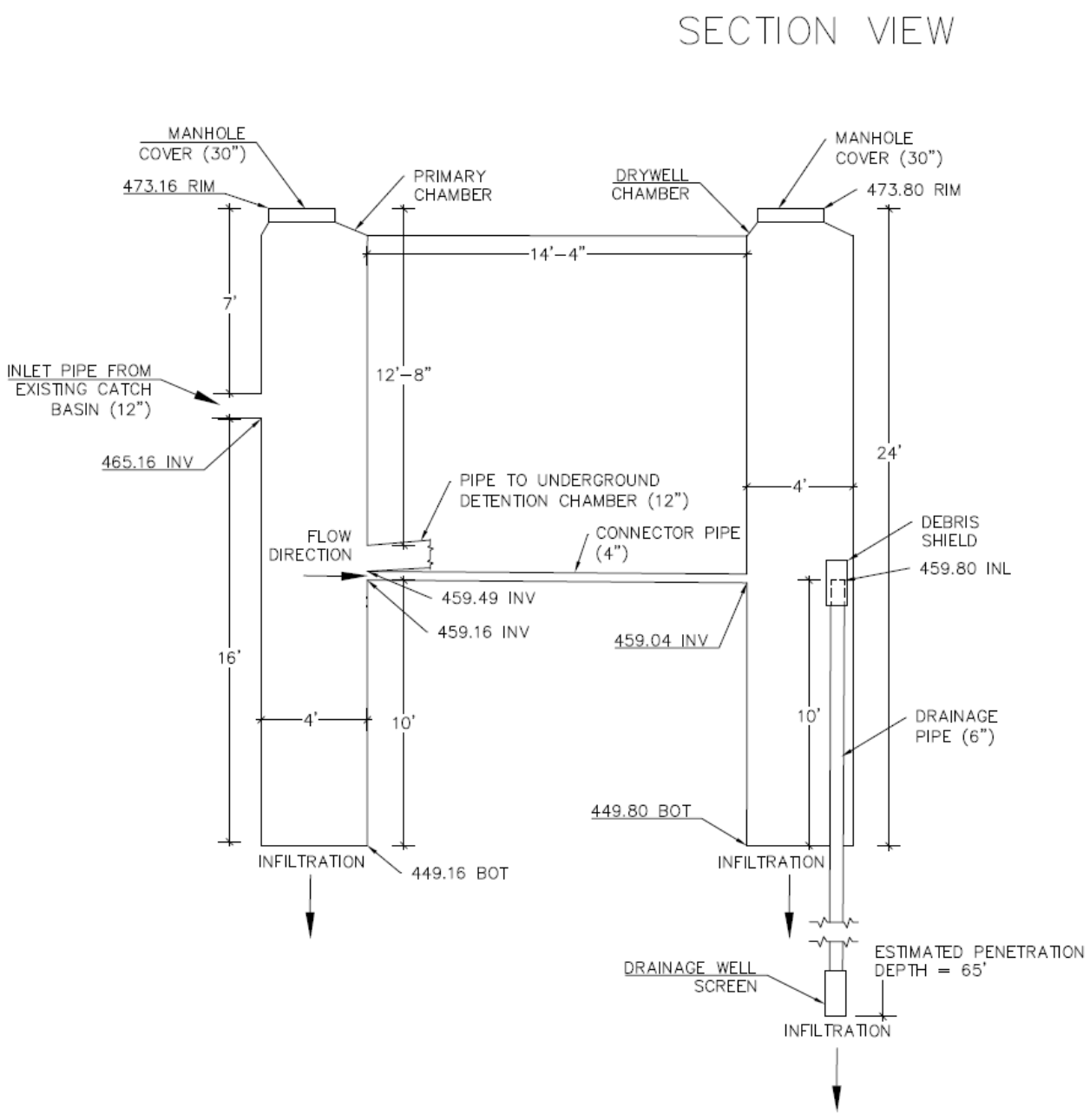

Figure 9.—Headquarters Drywell section view.

6.4 Van Nuys Bioretention and Drywell Details

The Van Nuys Green Streets Project includes a series of bioretention planters and drywells. The main components are: 1) pre-treatment bioretention planting, and 2) drywell chamber.

Stormwater runoff enters the bioretention area, which was not evaluated in this analysis, infiltrating via a perforated pipe or flowing through a non-perforated pipe to the drywell. In the drywell, water either infiltrates into the soil or is temporarily stored if infiltration capacity is exceeded.

6.4.1 Hydrogeological Setting

The Van Nuys Green Streets Project is situated in the San Fernando Groundwater Basin, with a vadose zone approximately 165 feet thick above the water table. The upper 5 feet are composed of fine sand, underlain by sand and a silty clay layer (8.5–18 feet), followed by sandy loam and sand to greater depths. Field borings and laboratory data indicate predominantly sandy textures with a significant silty clay interval that may locally restrict vertical flow. The site is not impacted by shallow groundwater or contamination, and the presence of thick, permeable sand layers below the silty clay supports rapid deep percolation to the aquifer. Two boreholes with neutron probes were installed to monitor infiltration and soil moisture responses during synthetic storm events



Figure 10.—Van Nuys Bioretention and Drywell.

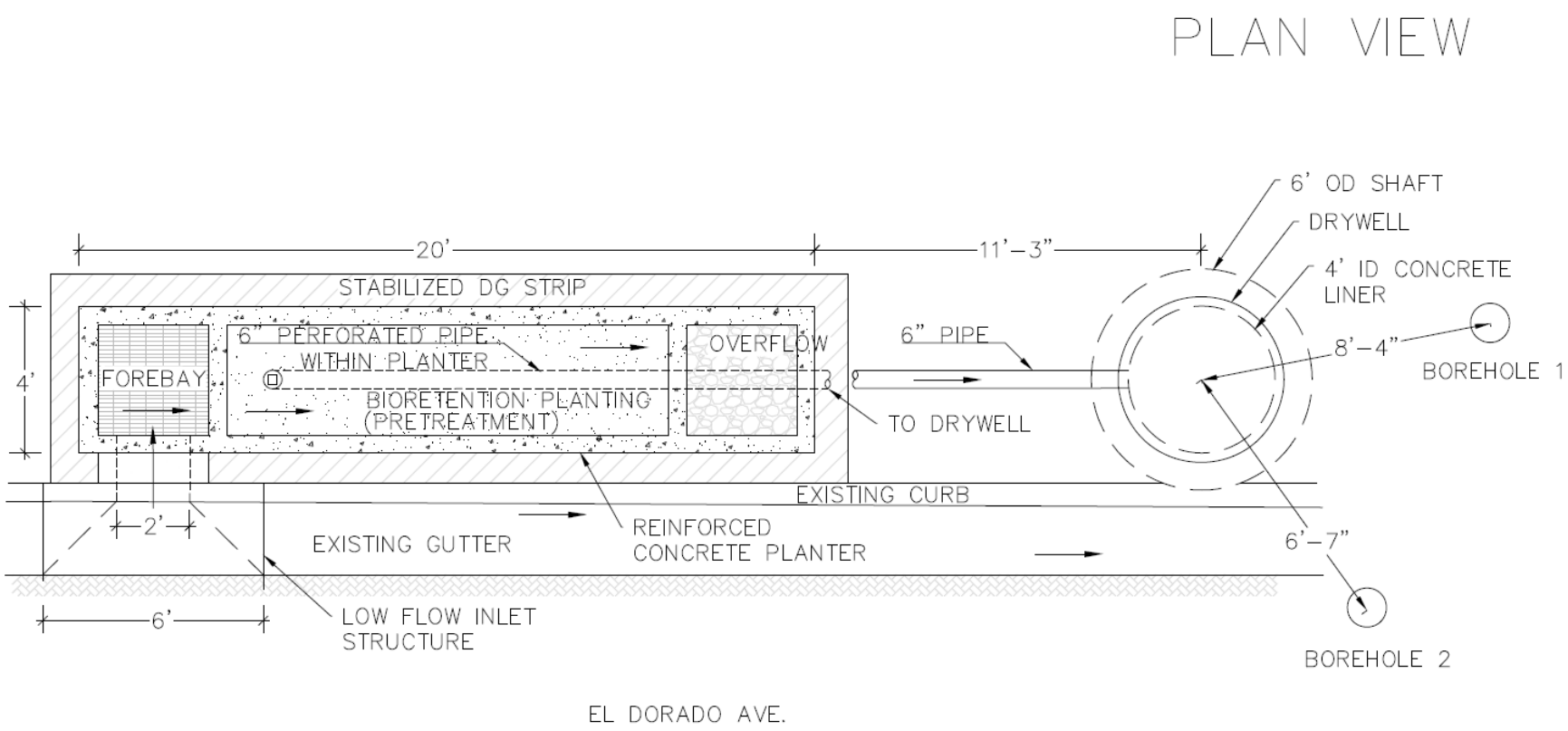

Figure 11.—Van Nuys Bioretention and Drywell plan view.

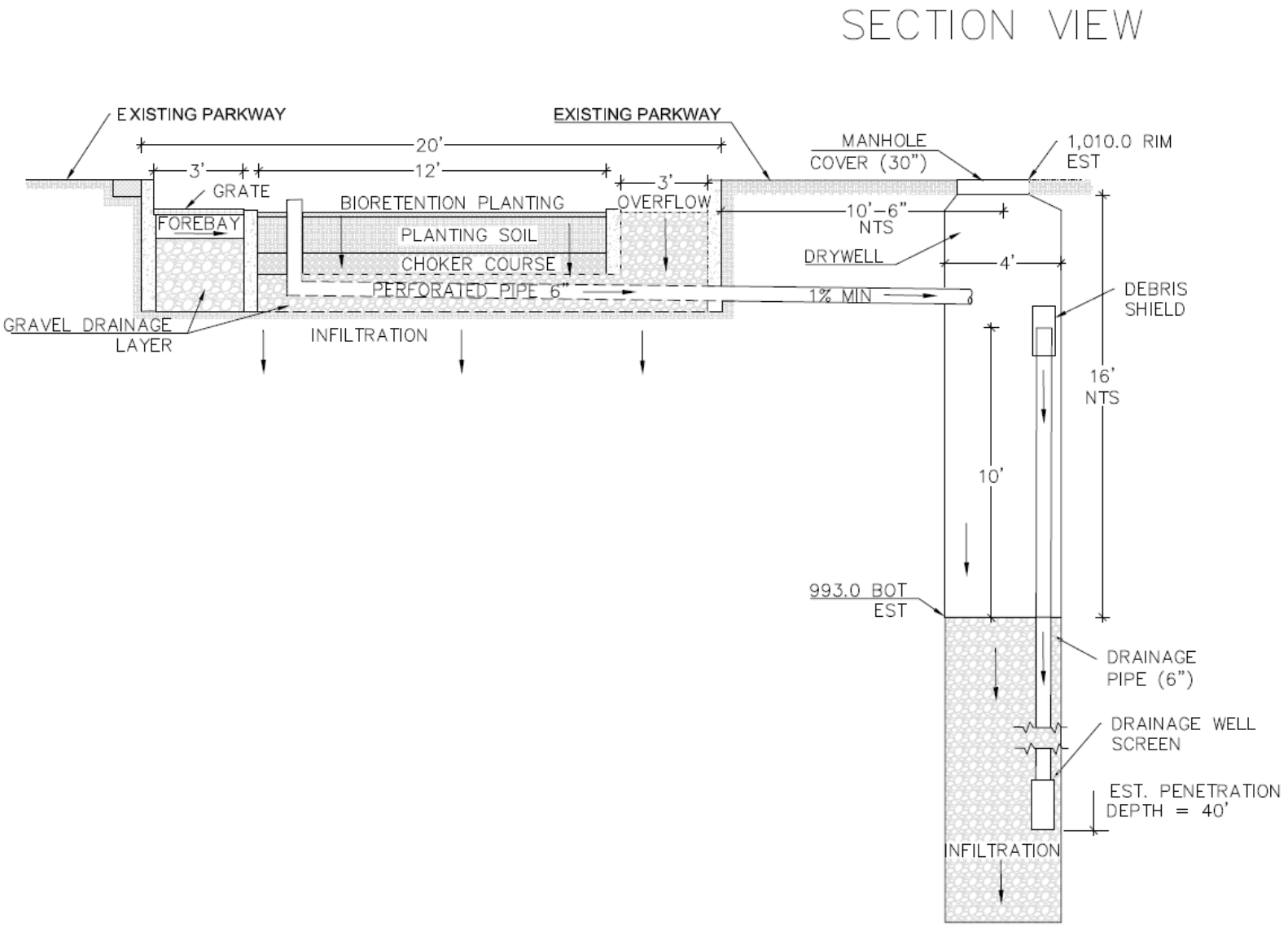

Figure 12.—Van Nuys Bioretention and Drywell section view.

7. Field Methods and Monitoring

7.1 Monitoring Approach

The monitoring approach for this study was designed to characterize subsurface infiltration behavior at each LID facility using a combination of geophysical imaging and direct soil-moisture measurements. The objective was to collect spatially and temporally resolved information on water movement beneath each BMP under controlled conditions that could later support hydrologic model calibration.

The monitoring program relied on paired installations of Electrical Resistivity Tomography (ERT) boreholes and neutron probe access tubes. ERT provided time-lapse imaging of how infiltrated water moved through the subsurface, while neutron probe measurements supplied vertical soil-moisture profiles that helped interpret ERT results and constrain hydraulic property estimates. The monitoring methodology is described in Appendix A3. Additionally, long-term monitoring data were collected following each simulated event.

7.2 Drilling and Instrumentation

Boreholes drilled to specified depths allowed for gathering in-situ soil data and for the installation of instrumentation into the subsurface. During the drilling process, Geosyntec Consultants representatives collected and documented soil samples in the field (see Figure 13), with some samples sent to a laboratory for further analysis. The lab reports included information on depths, blow counts, percent recovery, sample descriptions, and the composition of the samples (gravel, sand, fines). For certain samples, additional data on moisture content, dry density, and hydraulic conductivity were also provided (see Appendix A4). These data were later used to identify textural class names for model inputs.

Representatives from Lawrence Berkeley National Laboratory (LBNL) installed sensors by attaching them to PVC pipes, which were then placed into the boreholes. After installation, the space between each PVC pipe and the borehole wall was sealed with an appropriate material. Each borehole contained arrays of Electrical Resistivity Tomography (ERT) sensors, neutron probes, and temperature probes.

Rosemead Bioswale – Two boreholes instrumented with neutron probes were installed near the Rosemead Bioswale as shown in Figure 5.

Headquarters Drywell – Three boreholes instrumented with neutron probes were installed near the Headquarters Drywell as shown in Figure 8.

Van Nuys Green Streets Bioretention & Drywell – Two boreholes instrumented with neutron probes were installed near the Van Nuys Bioretention and Drywell as shown in Figure 11.



Figure 13.—Rosemead Blvd. drilling and soil sample collection.

7.3 Synthetic Storm Events

Synthetic storm events, or controlled simulations, were performed to monitor subsurface responses to added stormwater. Water volumes were measured using hoses with flow meters connected to fire hydrants. Table 2 includes the volumes for the synthetic storm events. The Headquarters LID had one event, Rosemead and Van Nuys LIDs each had two, but only Van Nuys' first event was included in the analysis.

Table 2.—Synthetic storm event volumes, durations, and observations

Site	Event	Date	Volume (ft^3)	Duration (hr)	Event Observations
Headquarters	1	8/28/21	3,743	6.0	Storage volumes and infiltration rates varied over time.
Rosemead	1	8/30/21	982	7.4	Average driving head = 0.46 ft
Rosemead	2	4/14/25	650	4.5	Average driving head = 0.33 ft
Van Nuys	1	4/16/25	5,300	3.0	Flow rates: 1) 0-1.23 hr; 1767.6 ft3/hr; 2) 1.23-2.96 hr; 1800 ft3/hr; 3) 2.96-24 hr; no flow.
Van Nuys	2	4/17/25	4,320	2.7	NA

For the Rosemead Bioswale, the synthetic storm events were conducted nearly four years apart, with no available maintenance records for the bioswale during this period. While site observations indicated no apparent changes in vegetation, sedimentation, or soil compaction, it is possible that antecedent soil moisture or unrecorded maintenance activities could have influenced infiltration conditions. As such, some uncertainty exists when comparing results between the two events.

For the Van Nuys Drywell, Event 2 was excluded from this analysis because it occurred shortly after Event 1. Event 1 was chosen for its undisturbed soil, yielding a clearer wetting-front signal.

7.4 Neutron Probe Volumetric Water Content Analysis

To monitor how water moved through the LID features during the synthetic storm events, neutron probes were installed in PVC access tubes at multiple subsurface depths. These instruments measure volumetric water content (θ) by emitting fast neutrons that were slowed down upon interacting with hydrogen atoms assumed to be from soil water. The measurement collected immediately before each synthetic storm event was used as the baseline, and subsequent readings were taken at set time intervals to track changes in soil moisture relative to that initial value.

Baseline θ values from all probes and depths at Rosemead (both storm events), Headquarters, and Van Nuys were reviewed to determine the normal level of measurement variability. Well-calibrated neutron probes typically exhibit about one percentage point of natural variation, so a threshold of 1.5 percentage points was used to ensure that observed increases exceeded normal instrument noise. Accordingly, any increase in θ greater than or equal to 1.5 percentage points was interpreted as a reliable indicator of true soil-moisture change rather than measurement fluctuation.

Appendix A6 contains the volumetric water content (θ) data readings from the neutron probes. Sections 7.4.1–7.4.3 include the analysis of this data.

7.4.1 Rosemead Bioswale

This section summarizes the volumetric water content analysis for both synthetic storm events.

Analysis of Neutron Probe Data for Borehole 1—Event 1

This section summarizes the depth-dependent changes in volumetric water content observed during the first synthetic storm event at the Rosemead Bioswale, highlighting the progression of the wetting front and peak moisture increases at each monitored depth.

Figure 14 shows the maximum positive peak Δθ values and corresponding depths at the Rosemead Bioswale.

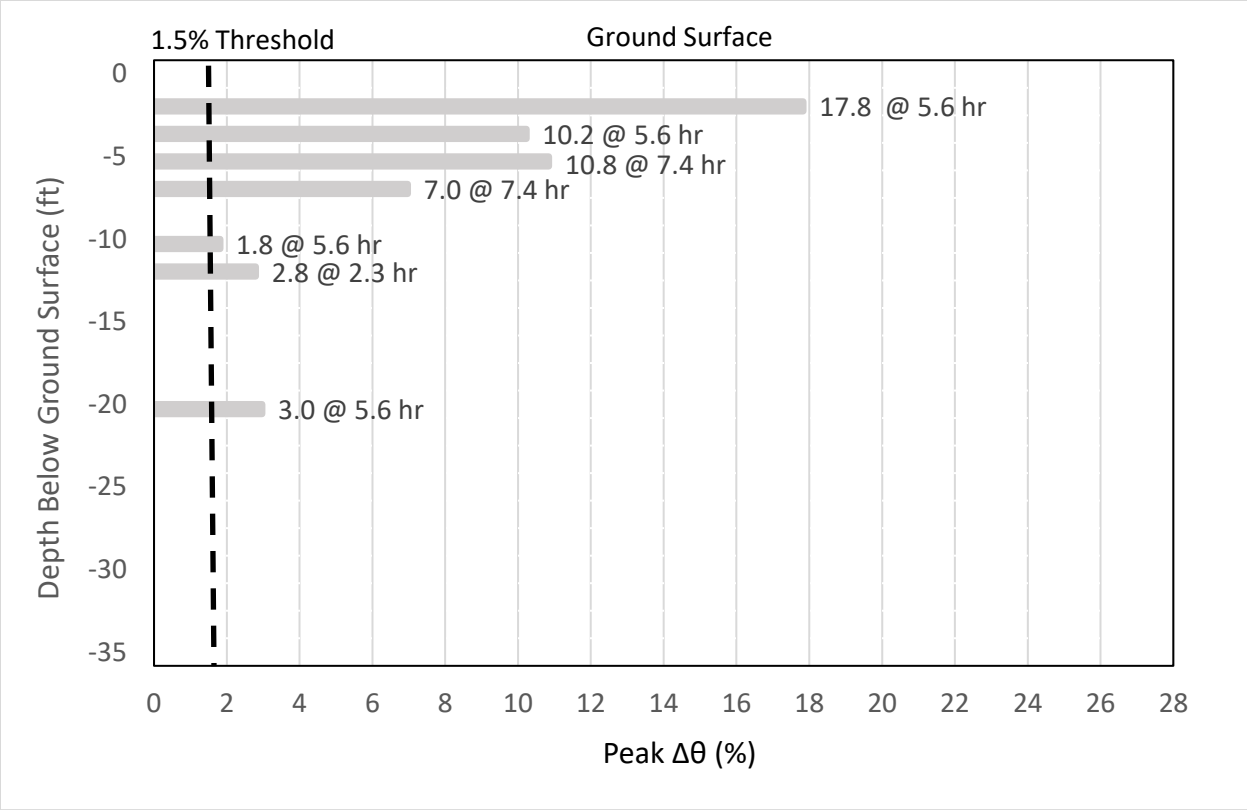

Figure 14.—Rosemead Bioswale: Borehole 1 (Neutron Probe 1) – maximum positive peak Δθ (%) by depth during Synthetic Storm Event 1.

Table 3 summarizes key observations from Figure 14, detailing volumetric water content increases at each monitored depth during and/or after the event.

Table 3.—Rosemead key observations for Borehole 1 (Neutron Probe 1) for Synthetic Storm Event 1

Depth (ft)	Key Observations
0.0 – 4.9	The shallow wetting front displayed a strong and rapid wetting response, with a continuous increase in moisture to 4.9 feet through 7.4 hours.
6.6	The shallow wetting front zone expanded downward over time.
9.8 – 11.5	Some mid-depth wetting increases observed.
19.7	Soil moisture significantly increased at 5.6 hours, possibly a local anomaly or stratigraphic effect.
21.3 – 32.8	Minor changes observed.

Analysis of Neutron Probe Data for Borehole 2—Event 1

Figure 15 shows the maximum positive peak Δθ values and corresponding depths observed at the Rosemead Bioswale.

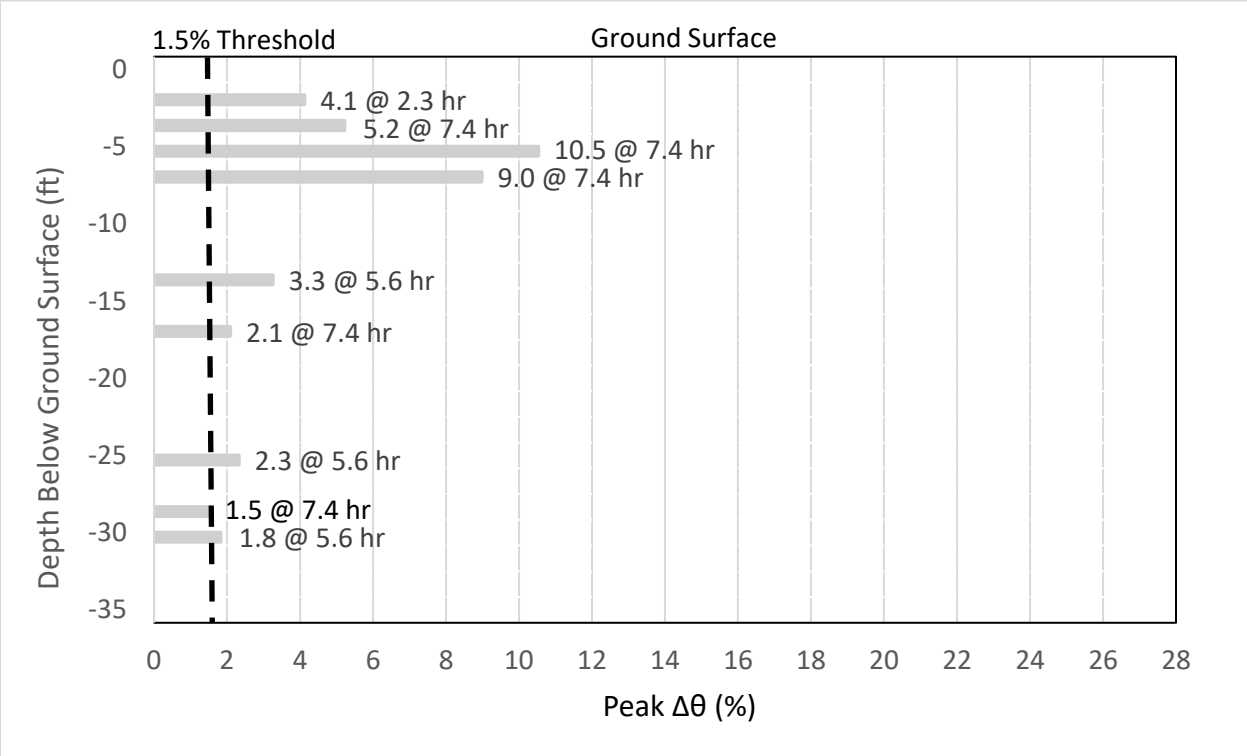

Figure 15.— Rosemead Bioswale: Borehole 2 (Neutron Probe 2) – maximum positive peak Δθ (%) by depth during Synthetic Storm Event 1.

Table 4 summarizes key observations from Figure 15, detailing volumetric water content increases at each monitored depth during and/or after the event.

Table 4.— Rosemead key observations for Borehole 2 (Neutron Probe 2) for Synthetic Storm Event 1

Depth (ft)	Key Observations
0.0 – 3.3	The shallow wetting front displayed a strong and rapid wetting response, with a continuous increase in moisture to 3.3 feet through 7.4 hours.
4.9 – 6.6	The shallow wetting front zone expanded downward over time.
9.8 – 16.4	Mid-depth wetting mostly increased at 13.1 and 16.4 feet, possibly caused by a local anomaly or stratigraphic effect.
24.6	Wetting increased slightly.
26.2 – 32.8	Minor increases were observed at some lower elevations.

Summary of Observations for Event 1

Both probes demonstrate strong infiltration near the surface (0.0 – 6.6 ft) and showed similar trends—rapid storage gains early, then slower increase. Both wetting profiles advanced and broadened at mid-depths, with additional moisture increases and possible drainage zones appearing near 20-25 ft. Wetting front velocity appears similar for both probes.

Analysis of Neutron Probe Data for Borehole 1—Event 2

This section summarizes the depth-dependent changes in volumetric water content observed during the second synthetic storm event at the Rosemead Bioswale, highlighting the progression of the wetting front and peak moisture increases at each monitored depth.

Figure 16 shows the maximum positive peak Δθ values and corresponding depths at the Rosemead Bioswale.

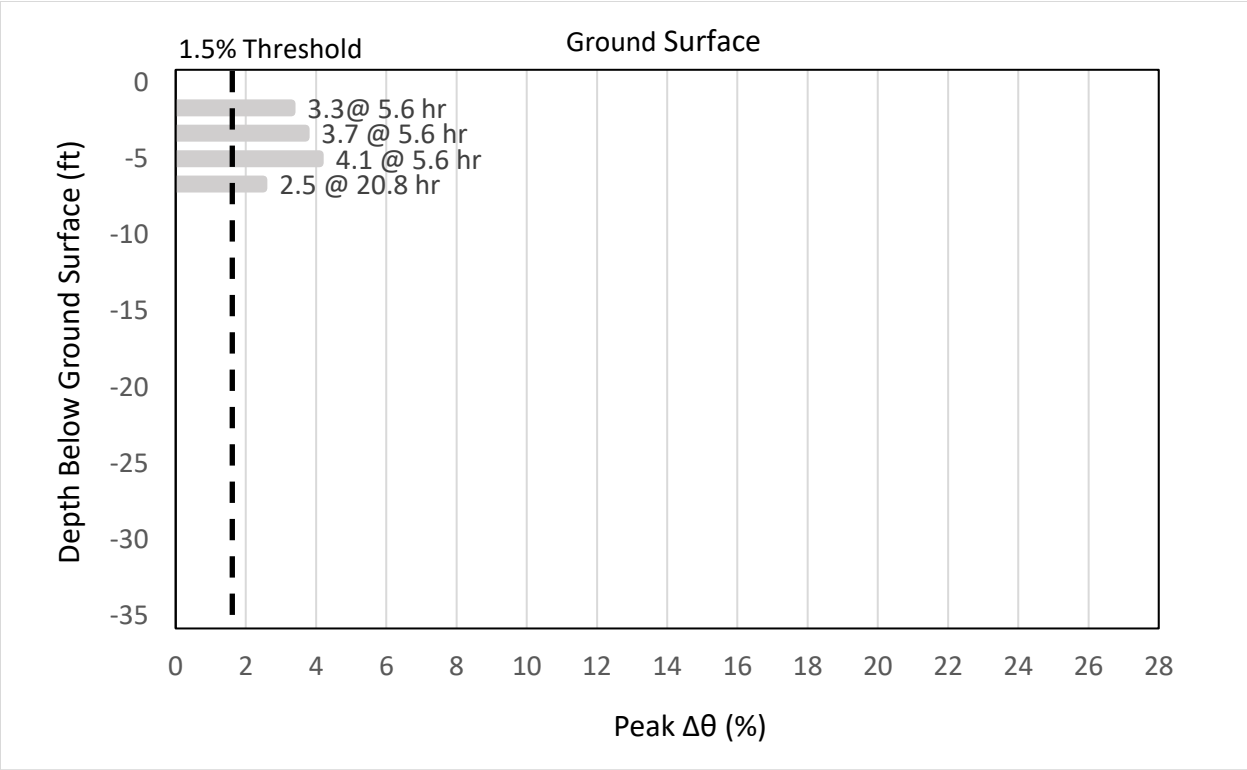

Figure 16.— Rosemead Bioswale: Borehole 1 (Neutron Probe 1) – maximum positive peak Δθ (%) by depth during Synthetic Storm Event 2.

Table 5 shows key observations and corresponding positive peak Δθ values.

Table 5.—Rosemead key observations for Borehole 1 (Neutron Probe 1) for Synthetic Storm Event 2

Depth (ft)	**Key Observations**
0.0 – 4.9	The shallow wetting front displayed a strong and rapid wetting response, with a continuous increase in moisture to 4.9 feet through 5.6 hours.
6.6	The shallow wetting front zone expanded downward over time.
8.2 – 27.9	Soil moisture was largely unchanged throughout the event.

Analysis of Neutron Probe Data for Borehole 2—Event 2

Figure 17 shows the maximum positive peak Δθ values and corresponding depths at the Rosemead Bioswale.

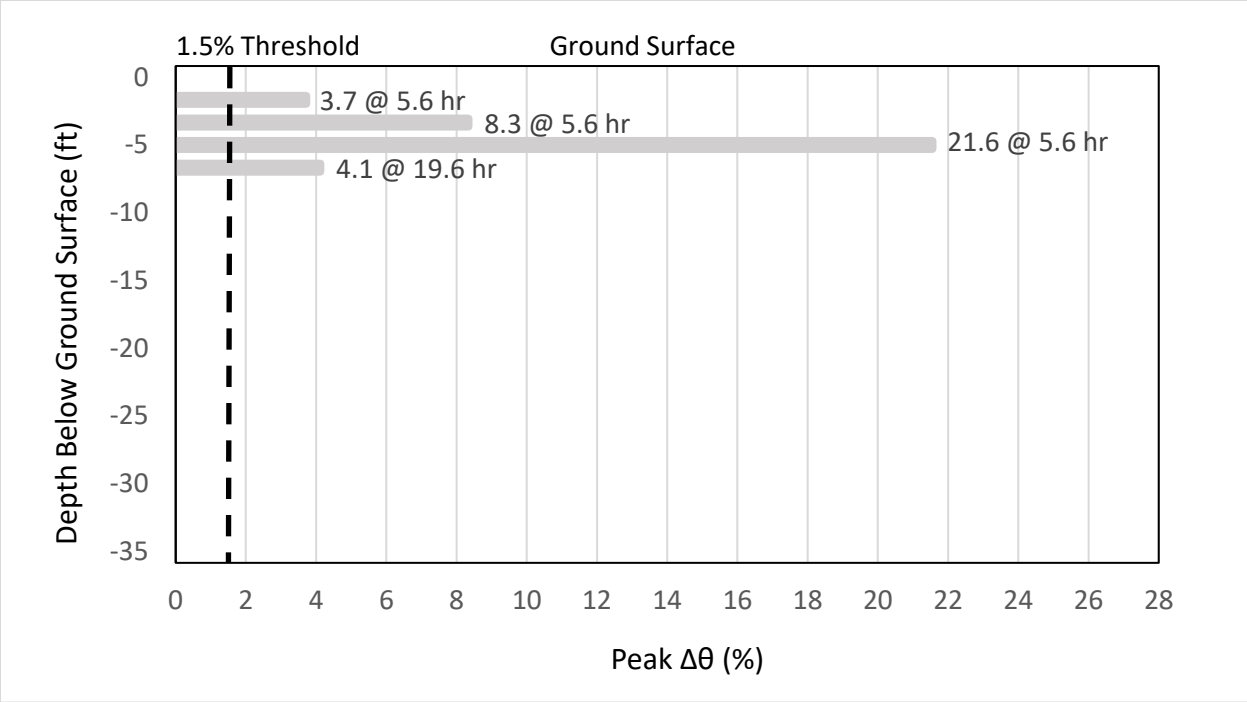

Figure 17.—Rosemead Bioswale Borehole 2 (Neutron Probe 2) – maximum positive peak Δθ (%) by depth during Synthetic Storm Event 2.

Table 6 shows key observations and corresponding positive peak Δθ values.

Table 6.—Rosemead key observations for Borehole 2 (Neutron Probe 2) for Synthetic Storm Event 2

Depth (ft)	Key Observations
0.0 – 6.6	The shallow wetting front exhibited a strong and rapid response, with moisture continuously increasing to a depth of 6.6 feet over 5.6 hours. Subsequently, soil moisture decreased within the 0 to 4.9-foot depths from 5.6 – 19.6 hours, while an increase was observed at the 6.6-foot depth.
8.2 – 29.5	Soil moisture largely unchanged throughout the event.

Summary of Observations for Event 2

Both probes show strong infiltration and wetting front stabilization in the upper approximately 6–7 feet. Probe 2 displayed a much stronger early wetting pulse (notably at 4.9 feet) and higher initial storage, suggesting preferential flow or differences in stratigraphy. Probe 1 retained slightly more

water over time, whereas Probe 2 lost significant storage by around 20 hours, indicating variability in redistribution and drainage across the bioswale.

7.4.2 Headquarters Drywell

This section summarizes the volumetric water content analysis for the synthetic storm event.

Analysis of Neutron Probe Data for Borehole 1

Figure 18 shows the maximum positive peak Δθ values and corresponding depths observed at the Headquarters Drywell.

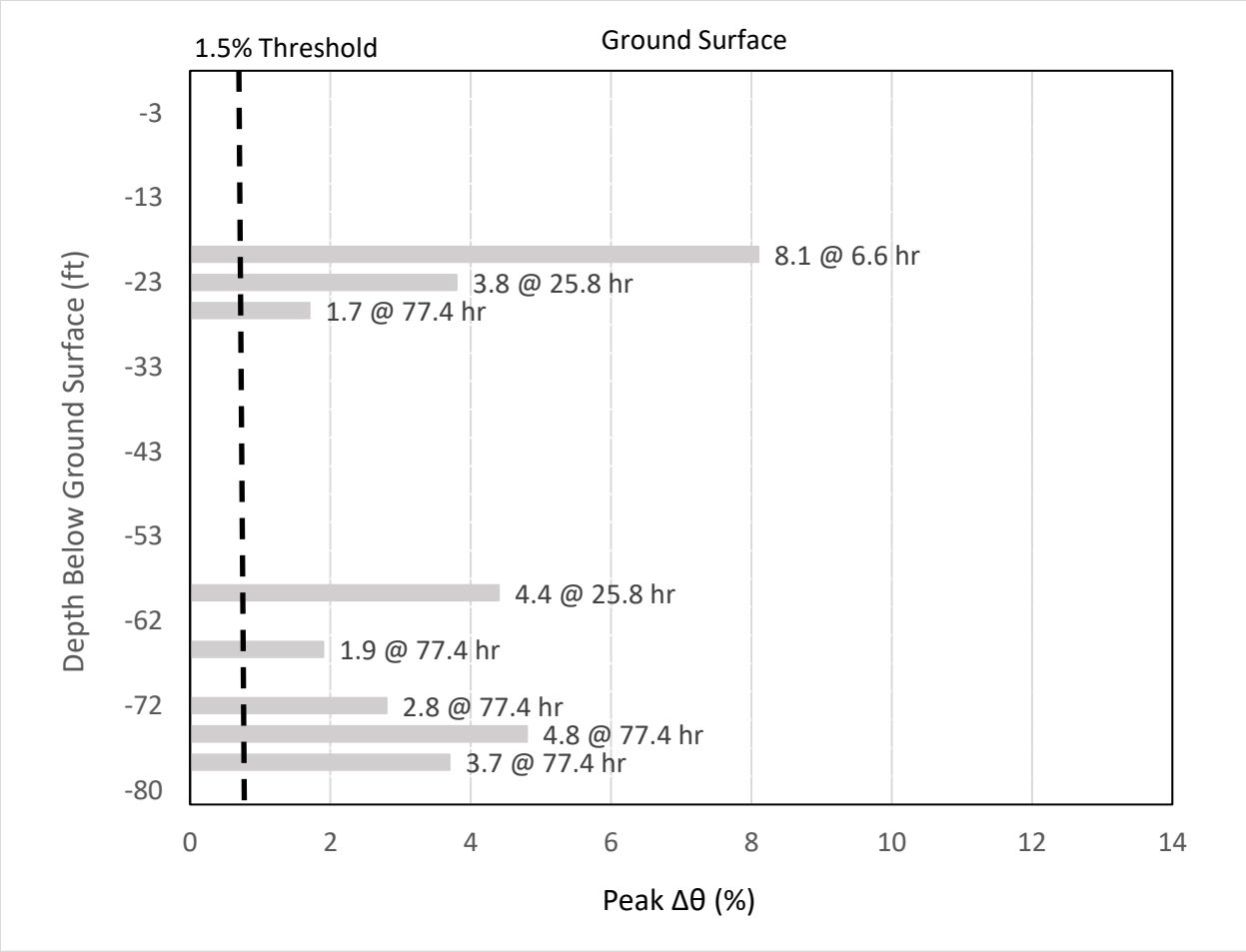

Figure 18.—Headquarters Drywell: Borehole 1 (Neutron Probe 1) – maximum positive peak Δθ (%) by depth.

Table 7 shows key observations and corresponding positive peak Δθ values

Table 7.—Headquarters key observations for Borehole 1 (Neutron Probe 1)

Depth (ft)	Key Observations
0.0 – 16.4	Shallow layers largely unchanged; θ stable with <±0.5-point variation throughout the event.
19.7	Strong mid-depth response at 4.7 hr sustained through 77.4 hr.
23.0	Mid-depth wetting front continuation downward over time.
59.1	Mid–deep response began at 20.6 hours.
65.6	Delayed deep wetting with peaks near 77.4 hr.
72.2 – 78.7	Delayed deep wetting with peaks near 77.4 hr.

Analysis of Neutron Probe Data for Borehole 2

Figure 19 shows the maximum positive peak Δθ values and corresponding depths observed at the Headquarters Drywell.

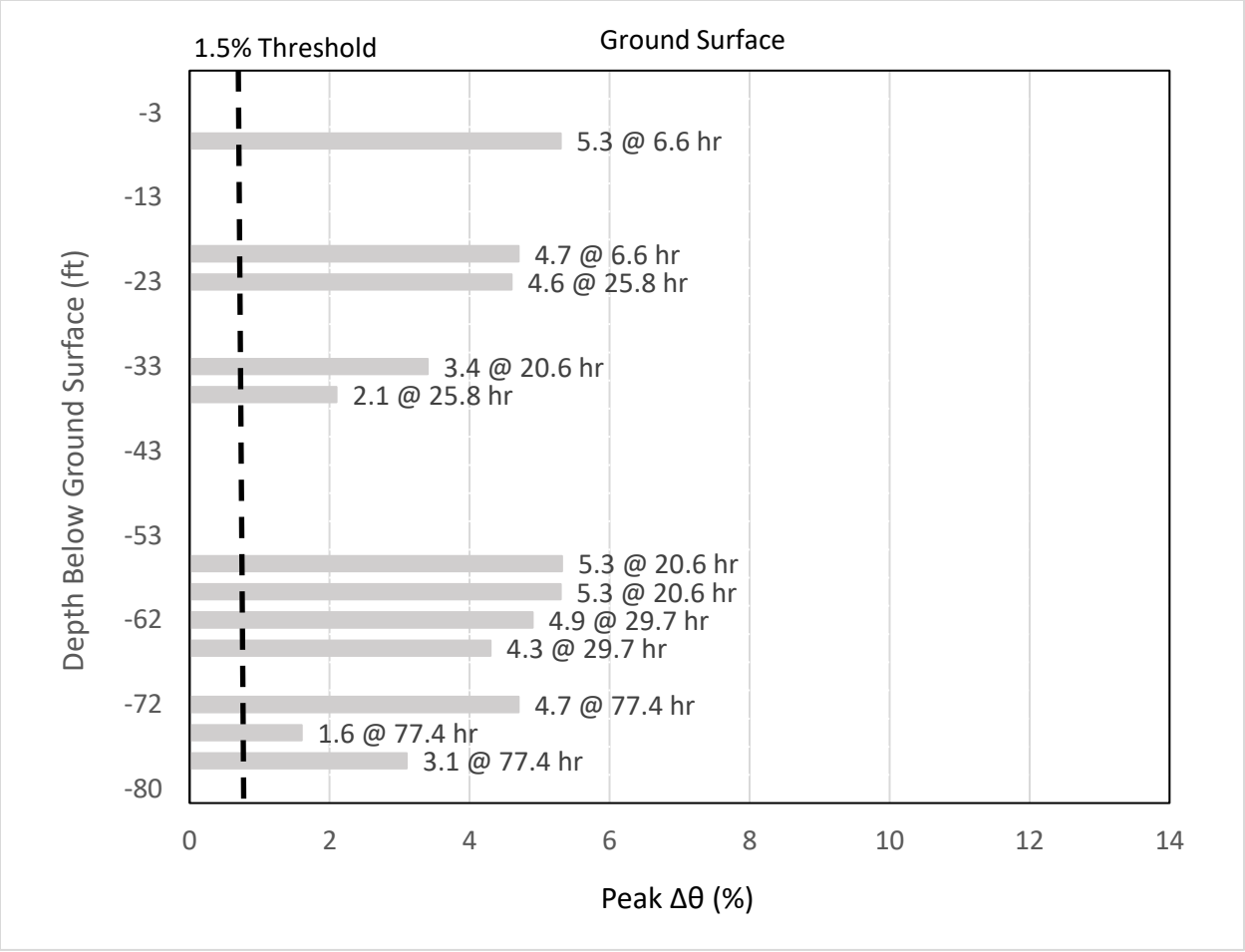

Figure 19.—Headquarters Drywell: Borehole 2 (Neutron Probe 2) – maximum positive peak Δθ (%) by depth.

Table 8 shows key observations and corresponding positive peak Δθ values.

Table 8.—Headquarters key observations for Borehole 2 (Neutron Probe 2)

Depth (ft)	**Key Observations**
0.0 – 16.4	Shallow layers remained largely unchanged, except at a depth of 6.6 feet, where there is an average increase of 4.8% in all neutron probe readings.
19.7 – 23.0	Early mid-shallow wetting beginning at 2.5 hours sustained through 77.4 hr.
32.8 – 36.1	Mid-deep wetting response begins at 6.6 hours.
55.8 – 59.1	Mid–deep response beginning at 20.6 hours.
62.3 – 65.6	Delayed deep wetting beginning at 25.8 hours.
72.2 – 78.7	Delayed deep wetting with peaks near 77.4 hr.

Analysis of Neutron Probe Data for Borehole 3

Figure 20 shows the maximum positive peak Δθ values and corresponding depths observed at the Headquarter Drywell

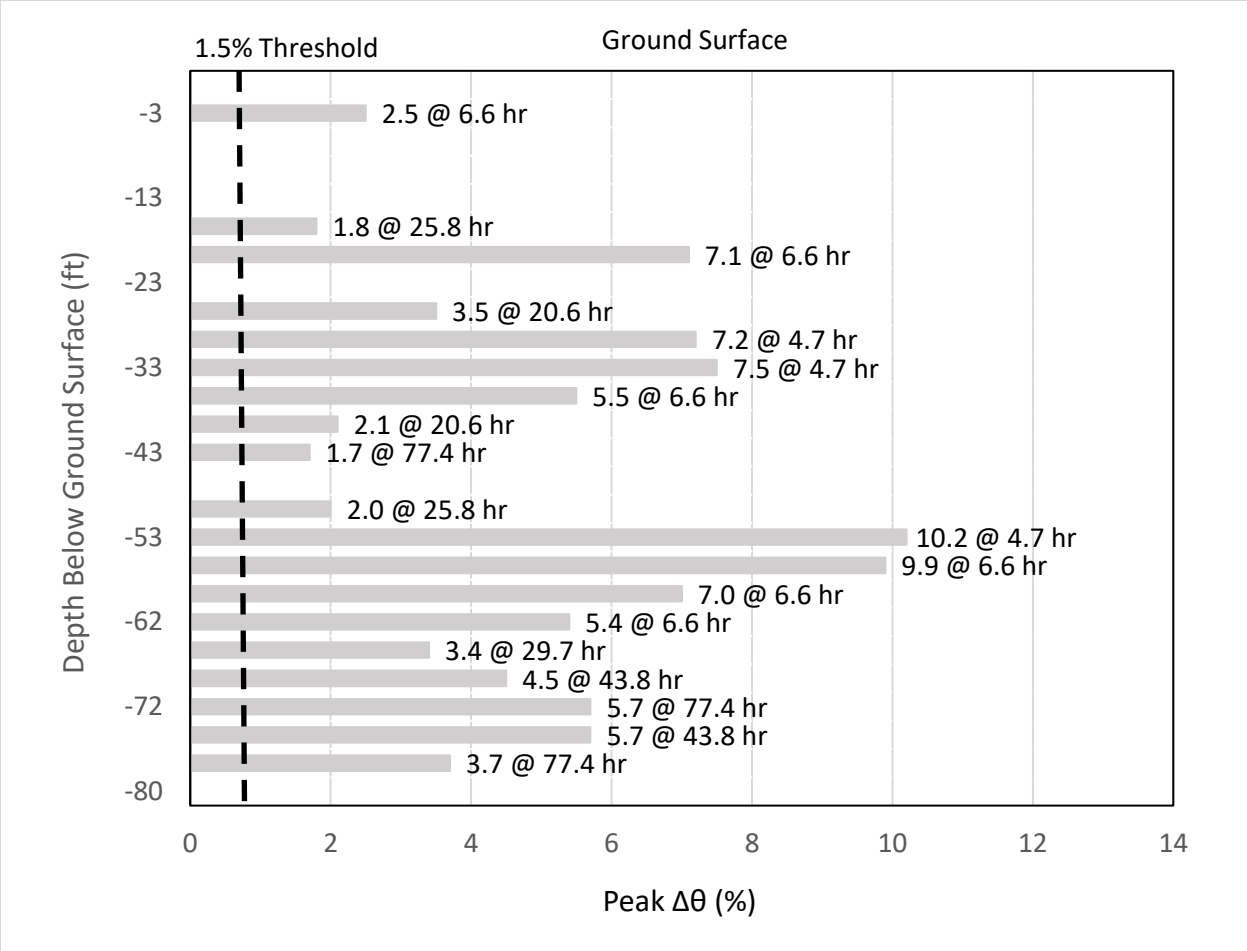

Figure 20.—Headquarters Drywell: Borehole 3 (Neutron Probe 3) – maximum positive peak Δθ (%) by depth.

Table 9 shows key observations and corresponding positive peak $\Delta\theta$ values.

Table 9.—Headquarters key observations for Borehole 3 (Neutron Probe 3)

Depth (ft)	Key Observations
0.0 – 16.4	Shallow wetting at 3.3 ft shows a modest early rise (11.0 → 13.5). 6.6 ft shows an anomalous decline (18.0 → ~12–13%), atypical for infiltration events which may indicate equipment malfunction or pre-event saturation anomaly. This observation was excluded from calibration targets.
16.4 – 19.7	Early mid-shallow wetting beginning at 2.5 hours sustained through 77.4 hours.
26.2 – 42.7	Mid-deep wetting response begins 2.5 – 4.7 hours with delayed wetting observed at lower range depths.
49.2 – 75.5	Deep wetting beginning mostly at 2.5 or 4.7 hours sustained through 77.4 hours.
78.7	Delayed deep wetting beginning at 43.8 hours.

Summary of Observations

The initial or baseline measurements, taken prior to the start of the synthetic storm event, show that volumetric water content in the soil across all three neutron probes (Boreholes 1, 2, and 3) generally ranged between 10% and 19% at most depths. Probe 3 shows the biggest increase in water content, reaching its highest point quickly, within about 2.5 to 4.7 hours, at certain depths. Probe 2 also has a strong peak but takes a little longer to arrive compared to Probe 1, around 6.6 hours. Probe 1 peaks early at a shallow depth, but at deeper levels, its water content rises slowly and reaches a high point much later, about 77 hours. Over time, mid-depth water increases at Probe 3 slowly drop back down, showing the soil is draining. Probe 2 water content remains elevated for approximately 30 hours after the storm event begins before declining, while the deepest layers monitored by Probe 1 take the longest to reach their peak moisture content. This pattern suggests that water moves more slowly and is retained longer at greater depths within the monitored soil profile.

7.4.3 Van Nuys Drywell

This section summarizes the volumetric water content analysis for the first synthetic storm event only.

Analysis of Neutron Probe Data for Borehole 1

Figure 21 shows the maximum positive peak Δθ values and corresponding depths observed at the Van Nuys Drywell.

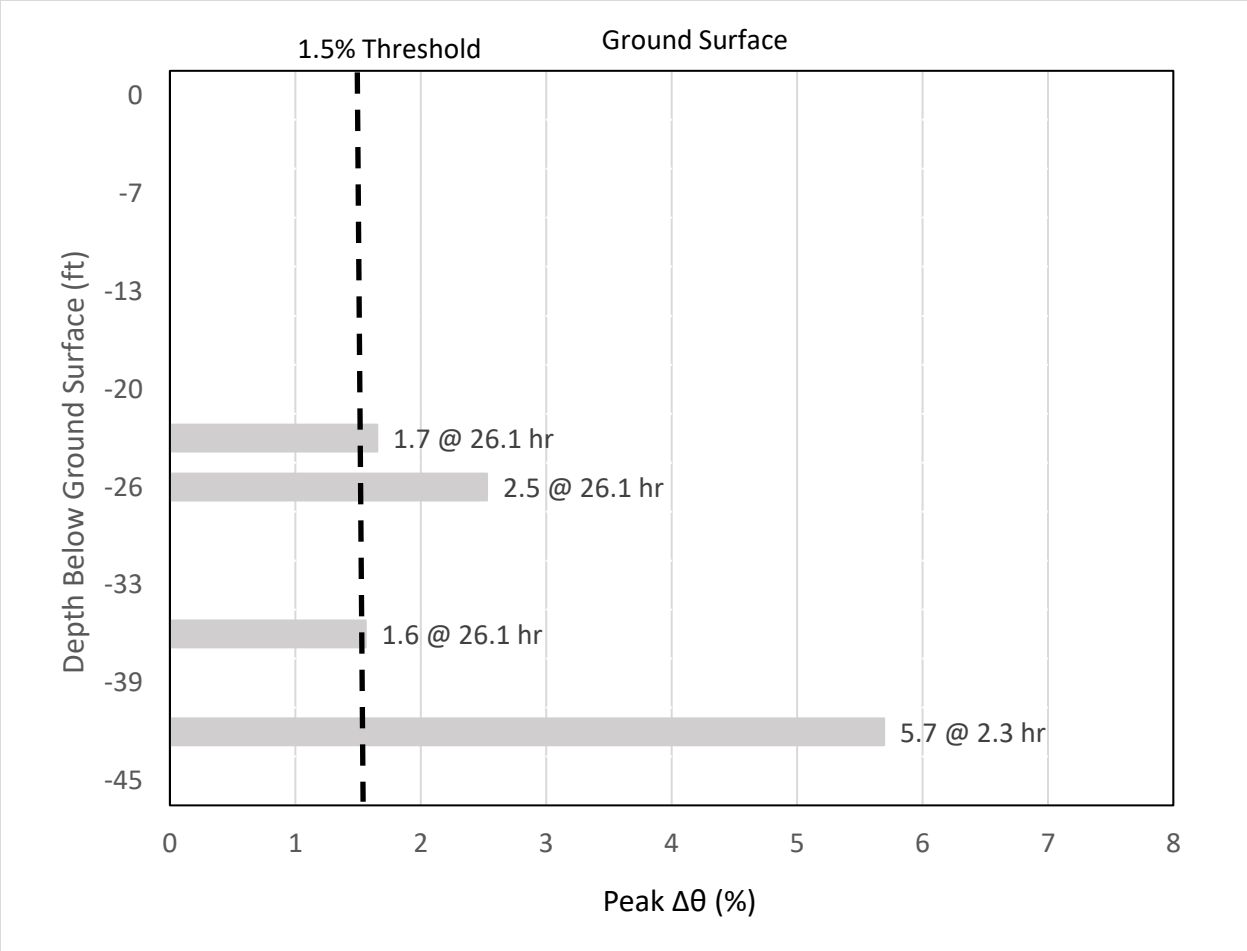

Figure 21.—Van Nuys Drywell: Borehole 1 (Neutron Probe 1) – maximum positive peak Δθ (%) by depth during Synthetic Storm Event 1.

Table 10 shows key observations and corresponding positive peak Δθ values.

Table 10.—Van Nuys key observations for Borehole 1 (Neutron Probe 1) for Synthetic Storm Event 1

Depth (ft)	Key Observations
0.0 – 19.7	Near-surface shows minimal change.
23.0 – 26.2	Mid-deep wetting response with moderate increases.
29.5 – 39.4	Deep wetting observed only at one time stamp with moderate increases.
42.7	Largest observations of deep wetting beginning at 2.3 hours.

Analysis of Neutron Probe Data for Borehole 2

No recorded maximum positive peak Δθ values were equal to or greater than 1.5 at the Van Nuys Drywell for Borehole 2.

Summary of Observations

Probe 1 shows depth-dependent variability in wetting response following the monitored event. Near-surface layers (0–19.7 ft) exhibited little to no measurable change, indicating limited infiltration in the upper profile. Moderate wetting occurred in the mid-depth interval from 23.0 to 26.2 ft, with increases up to +2.5% at 26.2 ft by 26.1 hours. A narrower deep interval (29.5–39.4 ft) displayed only single-time moderate increases, most notably +1.6% at 36.1 ft. The strongest response was observed at 42.7 ft, where a rapid and substantial moisture increase of +5.7% occurred as early as 2.4 hours, suggesting preferential flow or a permeable pathway at this depth.

Probe 2 showed minimal changes across the entire measured profile from 0.0 to 75.5 ft. No depth intervals exhibited meaningful increases, indicating that Probe 2 recorded negligible infiltration or redistribution during the monitoring period. This contrast between the two probes suggests significant lateral heterogeneity in subsurface conditions at the site, with localized differences in soil properties or structure likely controlling the observed infiltration patterns.

8. Infiltration Modeling Approach

This section describes the modeling tools that were used for this study. A summary of previously developed modeling tools applicable to this region can be found in Appendix A1 and Appendix A2.

8.1 Conceptual Models

For this study, conceptual models were developed to represent the key physical processes that control infiltration and deep percolation beneath each LID feature. The primary purpose of these conceptual models is to help answer fundamental questions about where, when, and why groundwater recharge occurs (Healy, 2010). As new data and analyses became available, the models were revised to incorporate updated understanding and site-specific insights (Zheng et al., 2002). These conceptual models form the basis for the numerical simulations and are tailored to reflect the geometry and hydraulic characteristics of each study site.

At both the Rosemead Bioswale and Headquarters Drywell sites, a two-dimensional (2D) Cartesian coordinate system was used for analysis. This approach was selected because the infiltration features at these locations—an elongated bioswale at Rosemead and two parallel drywell chambers at Headquarters—are best represented in plan view as rectangular or linear systems. The 2D Cartesian model effectively captures both vertical and lateral water movement along a horizontal plane, allowing for detailed simulation of infiltration dynamics and interactions between the engineered structures and surrounding soil.

At the Van Nuys site, a two-dimensional (2D) radial coordinate system was used for analysis. This approach was selected because the primary infiltration feature—cylindrical drywell—create an axisymmetric flow pattern, with stormwater entering at a central point and moving both vertically and radially outward through the surrounding soil. The 2D radial model accurately represents this circular symmetry and the resulting distribution of infiltration, providing a realistic simulation of water movement beneath and around the drywell.

The conceptual models developed for this study are shown in **Error! Reference source not found.**

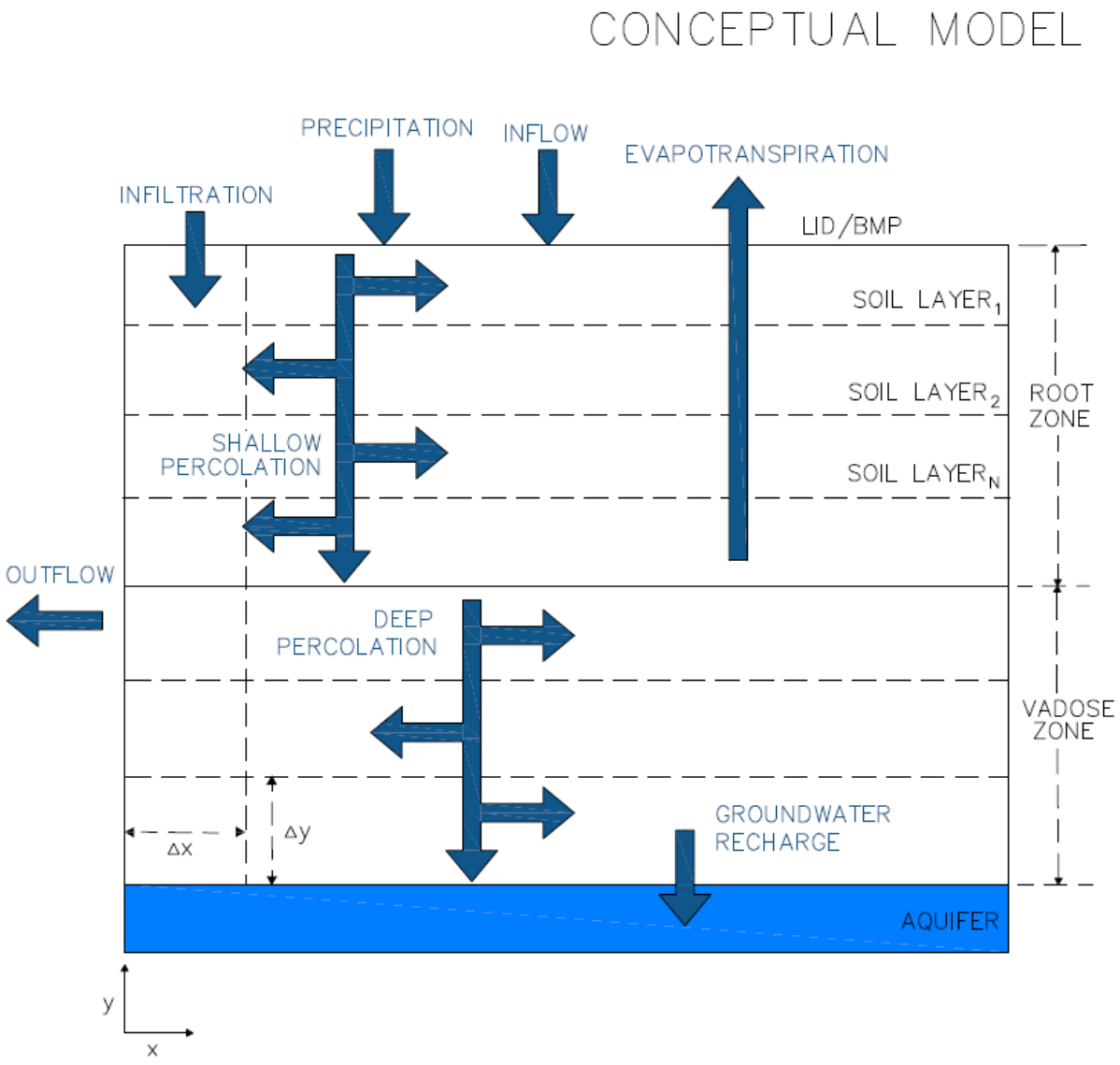

Figure 22.—Conceptual model of the Rosemead Bioswale and Headquarters Drywell.

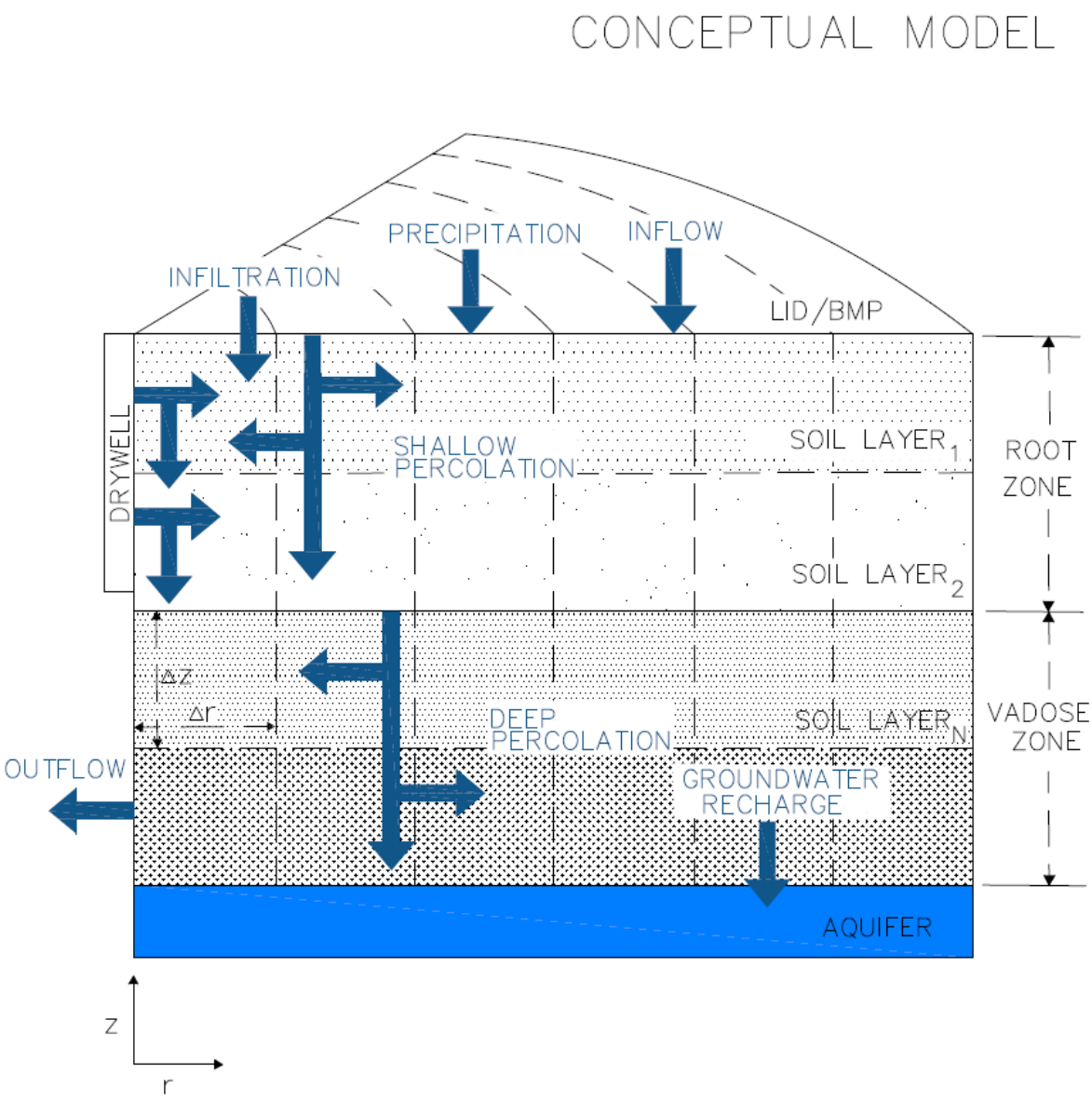

Figure 23.—Conceptual model of the Van Nuys Drywell.

8.2 Infiltration Models - VS2DI

8.2.1 Model Selection Criteria

The following three criteria were identified as essential for selection of the LA LID subsurface numerical modeling approach/tool:

- Capable of modeling the vadose zone;
- Detailed enough for sub-catchment scale; and
- Open source and current.

8.2.2 Overview of Selected Modeling Software: VS2DI

The VS2DI (Variably Saturated Two-Dimensional) package, developed by the USGS, was selected as the infiltration modeling tool for this study. VS2DI is open-source software designed to simulate water flow and solute or heat transport through variably saturated porous media (USGS, 2018). The software solves the Richards equation for unsaturated flow, allowing users to model both vertical and lateral movement of water through soil profiles under a range of boundary conditions. VS2DI supports both Cartesian and radial coordinate systems, making it suitable for simulating infiltration beneath features such as bioswales, drywells, and other stormwater management structures.

In addition to meeting the selection criteria listed above, VS2DI was chosen over other available numerical models because it provides an effective balance of capability, transparency, and efficiency for this project. Unlike simpler one-dimensional infiltration tools, VS2DI can represent both vertical and lateral flow processes, offering a more complete depiction of vadose-zone behavior. At the same time, it is significantly more efficient and easier to implement than complex three-dimensional or proprietary models, while still solving the full Richards equation and providing robust unsaturated flow simulations. Its open-source nature, published documentation, and long-standing use in hydrologic research further support its suitability for multi-scenario analysis within deep vadose zone settings. Together, these characteristics made VS2DI the most appropriate tool for the infiltration modeling performed in this study.

Key terms used in VS2DI include:

- **Anisotropy ratio:** ratio of vertical hydraulic conductivity to horizontal hydraulic conductivity (K_{zz}/K_{hh})
- **Boundary conditions:** Specifications of water flux, pressure, or head at the model domain edges, representing real-world infiltration scenarios.
- **Equilibrium profile:** An initial condition in which the soil moisture distribution is set according to a steady-state balance with the water table.
- **Pressure head (h):** The energy state of water in the soil, influencing flow direction and rate.

- **Recharge period:** time span during which boundary conditions (which include recharge rates) and stresses remain unchanged.

- **Saturated hydraulic conductivity (K):** A measure of the soil's ability to transmit water when fully saturated.

- **Volumetric water content (θ):** The fraction of soil volume occupied by water.

VS2DI features a graphical interface for building models, assigning soil properties, and visualizing results. It includes numerical modules for simulating flow and solute transport (VS2DT) and flow and heat transport (VS2DH) (Healy & Essaid, 2012). The software is widely used in hydrologic research and engineering to evaluate infiltration, recharge, and contaminant transport in the vadose zone.

8.3 Soil Classification

Soil classification was based on the lithologic composition—that is, the mineral content, grain size, and texture—of samples obtained during borehole drilling, following the *Reclamation Earth Manual* (Reclamation, 1998), the *Reclamation Engineering Geology Field Manual* (Reclamation, 2001), and other sources. Soil texture classes were assigned at specific depth intervals. With limited field data, interpolations were made between measured soil texture elevations to create model input layers at 0.5-foot intervals from the surface to the deepest observation point. VS2DI assigned default saturated hydraulic conductivity values using Van Genuchten or Carsel and Parrish (CP) parameters, in units ft/hr. During calibration, these values were adjusted as needed. Tables 11–13 show both the default and calibrated values for each soil texture class.

8.4 Model Development and Settings

This study used specific model settings based on soil texture class values from Geosyntec Consultants' reports and other sources, with interpolation for any gaps. Section 8.5 further details the calibration process, including adjustments unrelated to soil texture class.

8.4.1 Model Development in VS2DI

Infiltration models were developed for each LID site using a grid spacing of 0.5 feet in both horizontal and vertical directions. The model domain's width and depth varied for each site to minimize boundary effects. For initial hydraulic conditions, the equilibrium profile option was selected, which uses the Van Genuchten function to describe the relationship between soil water content, pressure head, and hydraulic conductivity. The Van Genuchten function is a widely used mathematical model that characterizes how water moves through unsaturated soils by relating soil moisture retention and hydraulic properties to soil suction (van Genuchten, 1980). This approach allows for realistic simulation of water movement in the vadose zone, especially under varying soil textures and moisture conditions.

Initial equilibrium profiles were based on a literature review of water table elevations near the project sites. Recharge periods—intervals where boundary conditions and stresses remain constant—were developed from synthetic storm event observations shown in Table 2 and set to exceed the duration of the synthetic storm events to capture post-application infiltration behavior. Hydraulic properties were developed from the soil classifications outlined in Section 8.3. Model development followed guidance and examples from USGS documentation and published tutorials on VS2DI (USGS, 2018).

8.4.2 Rosemead Bioswale Model Settings (2D Planar)

Two-dimensional planar models for the Rosemead bioswale were created in a rectangular (x-y) coordinate system, enabling simulation of water infiltration at depth intervals that correspond to neutron probe measurement locations, which served as model stations in VS2DI. The domain was sized to allow sufficient lateral (x-direction) and vertical (y-direction) movement of water while minimizing boundary effects. Evaporation and transpiration parameters were incorporated based on values from literature and VS2DI example applications (see Appendix A4.1).

During synthetic storm events, the model applied a specified total head to the upper horizontal boundary to represent the addition of stormwater to the bioswale. When no water was being added, this boundary was switched to a no-flow condition, simulating the absence of surface recharge. All other boundaries, except the designated water entry point, were set to no-flow. The initial equilibrium profile placed the water table at a depth of 217 feet (z-coordinate). For each synthetic storm event, the upper boundary condition reflected observed ponding depths in the LID: 0.46 feet for the first event and 0.33 feet for the second. In the model, these ponding depths were used as positive pressure heads at the soil surface, representing the height of water above the soil that drives infiltration. Only positive (ponded) heads were applied, ensuring infiltration was driven by ponded water rather than by capillary suction. Hydraulic conductivity values based on soil texture class were modeled as follows:

Table 11.—Rosemead Bioswale: soil texture class and hydraulic conductivity by depth (default vs. modeled)

Depth Range (ft)	Soil Texture Class	Default Saturated Hydraulic Conductivity - K (ft/hr)	Modeled Saturated Hydraulic Conductivity - K (ft/hr)
0.0 - 3.0	Loamy Sand CP	4.78E-01	4.78E+00
3.0 - 14.0	Sandy Loam	9.56E-02	4.78E-02
14.0 - 18.5	Sand CP	9.74E-01	9.74E-01
18.5 - 35.0	Sandy Loam	9.56E-02	4.78E-02
35.0 - 36.5	Sand CP	9.74E-01	9.74E-01

The Rosemead model's upper boundary excludes capillary suction, focusing on infiltration during and after surface ponding. While capillary-driven infiltration can be significant in the loamy sand surface layer before ponding, its effect is brief and minor compared to the total event. This simplification may slightly underestimate early infiltration but is consistent with standard stormwater modeling practice.

8.4.3 Headquarters Drywell Model Settings (2D Planar)

A two-dimensional planar model was developed for the Headquarters Drywell to simulate water infiltration using the x-y coordinate system allowing for the direct comparison of depth-specific volumetric water content (θ) increases at defined model stations. The model domain was sized to allow adequate lateral (x-direction) and vertical (y-direction) water movement while minimizing boundary effects. The left boundary was assigned at x = 0, with stationing increasing outward along the x-axis. Vertical infiltration was applied at y = 0 representing the ground surface beneath the paved parking lot, so evaporation and transpiration were not included.

Water entered the system through three pathways: the bottoms of the primary chamber, secondary chamber, and the drywell. For the primary chamber, water levels over time were calculated using a Bernoulli based formula from absolute pressure (kPa). For the drywell chamber, water levels were measured directly. These water levels for both chambers were then converted to volumes to define recharge periods for the simulation.

Water was assumed to spread uniformly from the drywells to the neutron probes. Because the neutron probe access tubes (NP1, NP2, NP3) were not aligned with the model plane, their measured radial distances from the chamber centers were projected onto the 2D model plane. These projected distances—10.2 feet for NP1, 7.4 feet for NP2, and 6.9 and 9.1 feet for NP3—were used as model stations (x values). Figure 24 illustrates these locations and the potential subsurface water movement paths. NP3, located between the primary and drywell chambers, likely detected moisture increases from both chambers, although the figure only shows water from the drywell chamber. When projected onto the model plane, its response reflects the combined influence of both chambers, introducing some spatial uncertainty. As a result, NP3 results are interpreted with qualification, but still provide valuable information on wetting front timing and progression.

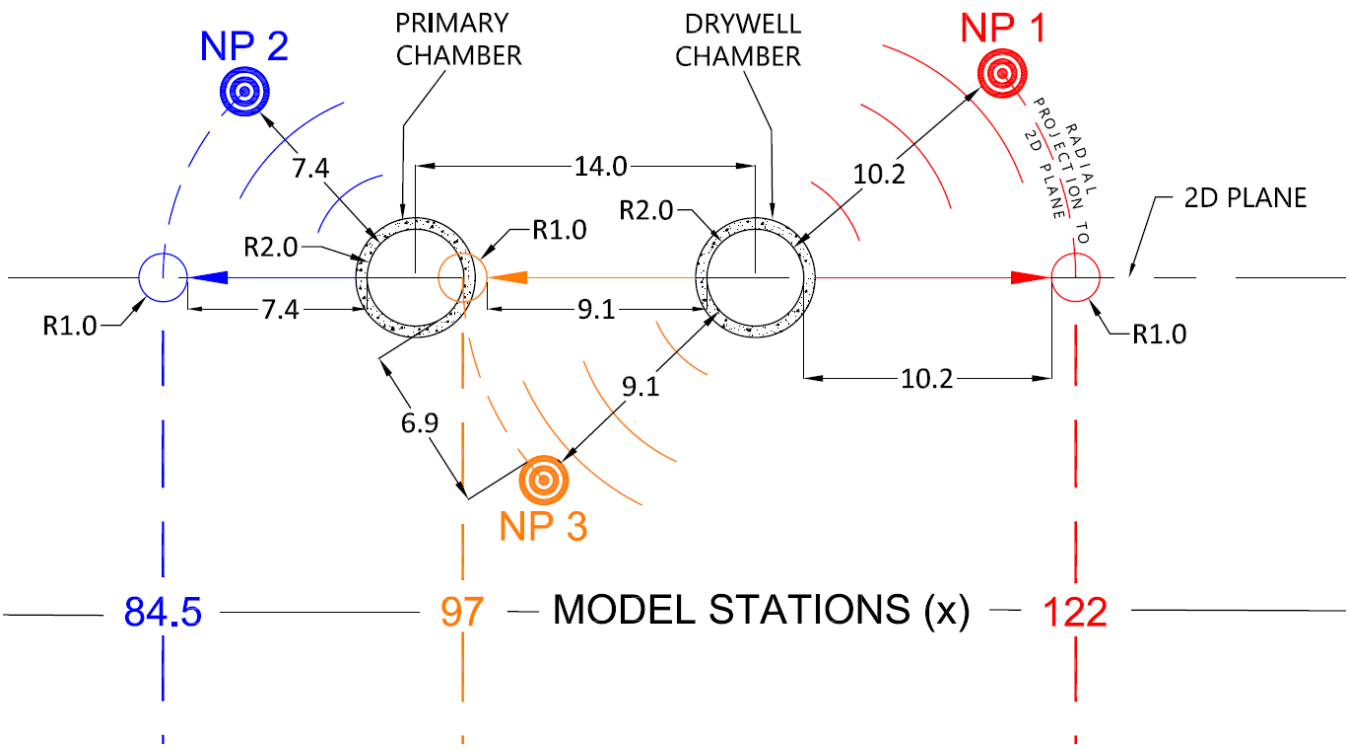

Figure 24.—Headquarters Drywell neutron probe locations and corresponding radial projections (drawn to scale).

All boundaries were assigned no-flow conditions, except at the primary chamber and drywell entry points, where either total head (h) or specified flux (q_n) was applied. Specified flux boundaries along the chamber sidewalls are consistent with published VS2DI applications for engineered structures, where lateral inflow is influenced by perforation geometry, gravel backfill, and soil properties rather than a fixed boundary head. This approach was necessary to accurately simulate lateral inflow at the Headquarters site.

Infiltration from engineered structures is rarely steady, as water surface elevations and hydraulic gradients change during storm events. To capture these dynamics, the simulation was divided into discrete recharge periods, each assigned a flux or total head reflecting observed chamber water levels for that interval. This method, commonly used in VS2DI models, allows the model to reproduce the observed timing and magnitude of moisture changes recorded by the neutron probes. The initial equilibrium profile placed the water table at a depth (z-coordinate) of 308 feet. Soil texture classes were modeled as described in Table 12.

Table 12.—Headquarters Drywell: soil texture class and hydraulic conductivity by depth (default vs. modeled)

Depth Range (ft)	Soil Texture Class	Default Saturated Hydraulic Conductivity - K (ft/hr)	Modeled Saturated Hydraulic Conductivity - K (ft/hr)
0.0 - 4.5	Sandy Loam CP	1.45E-01	1.45E-02
4.5 - 8.5	Sandy Clay Loam CP	4.30E-02	4.30E-02
8.5 - 21.0	Sandy Loam CP	1.45E-01	1.45E-02
21.0 - 28.0	Silt Loam	3.07E-02	3.07E-02
28.0 - 43.5	Sandy Loam CP	1.45E-01	1.45E-02
43.5 – 48.5	Silt Loam	3.07E-02	3.07E-02
48.5 - 53.5	Silt CP	8.19E-03	8.19E-03
53.5 - 58.5	Loam CP	3.41E-02	3.41E-02
58.5 – 63.5	Loamy Sand CP	4.78E-01	4.78E-01
63.5 – 68.5	Clay CP	6.57E-03	6.57E-03
68.5 – 73.5	Sandy Clay Loam CP	4.30E-02	4.30E-02
73.5 – 78.5	Silty Clay Loam CP	2.29E-03	2.29E-03
78.5 – 85.0	Sandy Loam CP	1.45E-01	1.45E-02
PRIMARY CHAMBER BACKFILL			
0 – 15.5	Silty Clay CP	6.57E-04	6.57E-08
DRYWELL CHAMBER BACKFILL			
0.75 – 14.5	Silty Clay CP	6.57E-04	6.57E-08

Geometric Simplification and Model Limitation:

The use of a 2D Cartesian coordinate system for the Headquarters Drywell introduces a geometric simplification. The actual chambers are cylindrical and produce a radially symmetric flow field more accurately represented by an axisymmetric (r-z) model. In the Cartesian framework, infiltrating sources are implicitly treated as infinite line sources rather than cylindrical point sources, which may affect computed flux distributions and deep percolation estimates. This limitation should be considered when interpreting the Headquarters deep percolation rates. The choice of a 2D Cartesian model was made to facilitate direct comparison with neutron probe data and to maintain consistency with the modeling approach used for the Rosemead Bioswale, but users should be aware that this simplification may influence the spatial distribution of simulated infiltration and recharge beneath the Headquarters Drywell.

The Headquarters Drywell model also excludes capillary suction at the upper boundary, focusing on infiltration driven by surface or chamber water levels. Although capillary-driven infiltration may occur in the unsaturated zone before significant ponding, its influence is brief and minor relative to the total event. This approach may slightly underestimate early infiltration but aligns with standard practice for modeling engineered infiltration systems.

8.4.4 Van Nuys Green Drywell Model Settings (2D Radial)

A two-dimensional radial model was developed to simulate water movement within a cylindrical domain under axial symmetry, utilizing the r–z coordinate system. In this setup, the bioretention

area drains directly into the drywell, which serves as the primary point of infiltration. Since the synthetic storm event applied water only at the drywell, the model concentrated exclusively on this feature. The domain was sized to ensure adequate lateral (r-direction) and vertical (z-direction) water movement while minimizing boundary effects. The left boundary was set at r = 0 (the center of the drywell), with radial stationing extending outward, and vertical infiltration modeled from z = 0 at the ground surface. Evaporation and transpiration were excluded since most of the domain is unaffected. All boundaries were assigned no-flow conditions except at the drywell, where a specified volumetric inflow was applied and varied by recharge period to accurately represent observed flow conditions as seen in Appendix A5.

During the synthetic storm event, water was introduced into the drywell as the event progressed, but this did not generate a driving hydraulic head within the drywell and was therefore not included in the modeling. The initial equilibrium profile placed the z-coordinate of the water table at 165 feet. Soil texture classes were incorporated into the model as follows (see Table 13).

Table 13.—Van Nuys Drywell: soil texture class and hydraulic conductivity by depth (default vs. modeled)

Depth Range (ft)	Soil Texture Class	Default Saturated Hydraulic Conductivity - K (ft/hr)	Modeled Saturated Hydraulic Conductivity - K (ft/hr)
0.0 - 5.0	Fine Sand	2.87E-01	2.87E-01
5.0 - 8.5	Sand CP	9.74E-01	9.74E-01
8.5 – 18.0	Silty Clay CP	6.57E-04	6.57E-07
18.0 – 53.5	Sandy Loam	9.56E-02	9.56E-02
53.5 – 58.5	Fine Sand	2.87E-01	2.87E-01
58.5 - 63.5	Sandy Loam	9.56E-02	9.56E-02
63.5 - 77.0	Sand CP	9.74E-01	9.74E-01

Rationale for Modeling Approach:

While a radial coordinate system was used for the Van Nuys Drywell given its single cylindrical geometry, the Headquarters system's two parallel chambers and off-axis neutron probe arrangement made direct application of a single radial model less straightforward. The 2D Cartesian approach was adopted as a practical simplification, with the understanding that it introduces geometric approximation relative to the true radial flow field. This difference in modeling approach was chosen to best match the physical layout and instrumentation of each site, but users should be aware that the geometric simplification at Headquarters may influence the spatial distribution of simulated infiltration and recharge.

8.5 Calibration

8.5.1 Calibration Overview

The primary goal of the modeling effort was to use site-specific field data to estimate deep percolation that could not be measured directly. Because percolation below the instrumented depth cannot be observed in the field, calibrated infiltration models provide the only practical method for projecting how much of the applied synthetic rainfall migrated downward toward the water table and contributed to recharge.

Calibration involved adjusting model inputs so simulated infiltration patterns matched the observed changes in volumetric water content (θ) measured by neutron probes the synthetic storm event (Healy, 2010). Many parameters governing variably saturated flow cannot be measured directly at depth; therefore, they were constrained through calibration using site-specific soil textures, observed water-level changes in the chambers, and θ responses at each LID site.

This approach supports the overarching project objectives: (1) to obtain field data needed to characterize deep percolation beneath different LID BMP types, and (2) to develop modeling tools capable of estimating deep percolation—and thus potential recharge—from BMPs under simulated storm conditions.

8.5.2 Calibration Parameters and Targets

The VS2DI model required several input (independent) parameters, including saturated hydraulic conductivity (K), initial distributions of water content or pressure head, and spatial and temporal boundary conditions. During calibration, the model's dependent (output) variables—primarily simulated volumetric water content (θ) and pressure head (h)—were compared to observed values from neutron probe measurements. Calibration was achieved by adjusting input parameters, most notably saturated hydraulic conductivity, so that the simulated outputs (θ, h) aligned with observed data. Among the input parameters, saturated hydraulic conductivity typically has the greatest influence on model results and often requires the most adjustment. It is not uncommon for calibrated values of hydraulic conductivity to differ from those obtained through field measurements (Healy & Essaid, 2012).

The calibration targets for each model are listed below:

Table 14.—Calibration parameters, wetting front targets, and justifications

LID Name	Calibration Parameters & Wetting Front Targets	Justification
Rosemead Bioswale	Event 1: Target infiltration depth = 6.5 feet at 7.4 model hours after model run begins. Event 2: target infiltration depth = 6.5 feet at 4.5 hours after model run begins.	Events 1 & 2: Both neutron probes showed significant volumetric water content (θ) increases from the surface to a depth of 6.5 feet during the synthetic storm event.
Headquarters Drywell	Targets (horizontal & vertical) were developed to align with infiltration along a plane linking the drywell's centers (see Figure 24 for details). NP1: • @ 4.7 hrs; x = 122, y = 19.5. NP2: • @ 2.5 hrs; x = 84.5, y = 19.5 (upper) & 23.0 (lower). • @ 6.6 hrs; x = 84.5, y = 56.0 (upper) & 59.0 (lower). NP3: • @ 2.5 hrs; x = 97.0, y = 49.0 & 78.5.	Water was assumed to spread uniformly from the drywells to the neutron probes. NP1 showed θ increases from the Drywell Chamber water, setting calibration targets accordingly. NP2 showed θ increases from the Primary Chamber water, establishing corresponding calibration targets. NP3 may have shown θ increases from either chamber. NP2: The target range was defined with specific upper and lower limits.
Van Nuys Bioretention & Drywell.	Target infiltration depths and radial widths were based on neutron probes 1 & 2. Upper infiltration target = 19.5 @ 2.27 hrs after model run begins. Lower infiltration target = 42.7 @ 2.27 hrs after model run begins. Radial target ≥ 7.3 feet @ 2.3 hrs.	The observed percentage increase in θ was equal to or greater than 2.0% between probe readings from 0 to 2.3 hours. This trend continued with percentage increases through probe readings up to 27.4 hours. NP2 also demonstrated some increases in θ, although these results were less definitive. The radial target was established to achieve or surpass the designated distance as determined by neutron probe measurements.

Figure 25 shows the profile view of the Headquarters Drywell system including where the projected neutron probe model stations align with the horizontal and vertical infiltration targets. The infiltration targets shown in red (NP1), blue (NP2), and orange (NP3) are described in Section 8.4.3.

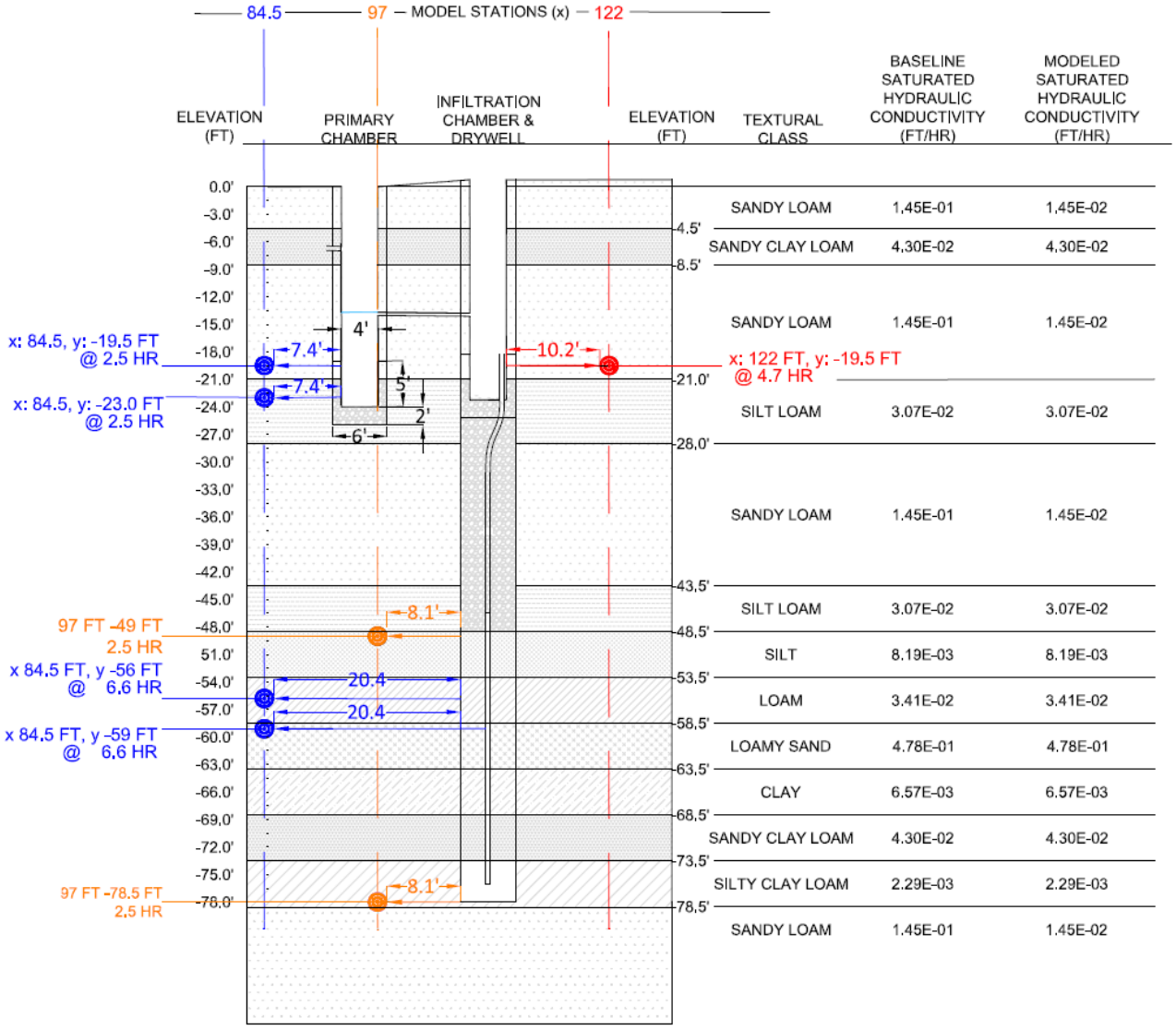

Figure 25.—Headquarters Drywell calibration targets and hydraulic conductivities by depth.

8.5.3 Calibration Adjustments

The following adjustments were made to meet the calibration targets in Section 8.5.2.

Spatial Alignment:

- Identified observation locations along the wetting front for radial or linear offsets and depths.

- Established baseline boundary conditions

Hydraulic Response Iteration:

- Manually modified the movement of the wetting front through soil (e.g., saturated hydraulic conductivity and anisotropy ratios) including radial or linear offsets and depths to match moisture spikes with neutron probe data. Adjustments were made step by step, with each iteration informed by previous results to ensure alignment with calibration targets.

- Adjusted boundary conditions (e.g., size, location, pressure, and flow rate per unit area).

The model was considered calibrated once the timing of the wetting front matched significant soil moisture increases in neutron probe data at specific elevations. Table 15 summarizes the model calibration variables and other adjustments.

Table 15.—Model calibration variables and adjustments

Model	Calibration Variables & Adjustments
Rosemead Bioswale	**Category:** Textural Class **Adjustments:** Saturated Hydraulic Conductivities • Sandy Loam: Changed saturated hydraulic conductivity to be less conducive to flow (from 9.56E-02 to 4.78E-02). • Loamy Sand CP: Changed saturated hydraulic conductivity to be more conducive to flow (from 4.78E-01 to 4.78E+00).
Headquarters Drywell	**Categories:** Boundary Conditions, Textural Class **Adjustments:** Anisotropy Ratios, Saturated Hydraulic Conductivities, Specified Flux, Specified Total Head Boundary Conditions: • Adjusted Specified Flux Into Domain (x) and/or Specified Total Head (y) where necessary. Textural Class • Sandy Loam CP: Changed saturated hydraulic conductivity to be less conducive to flow (from 1.45E-01 to 1.45E-02). Changed anisotropy ratio (K_{zz}/K_{hh}) from 1 to 0.3 to force water outward from the drywell. • Silt Loam & Silty Clay Loam: Changed anisotropy ratios (K_{zz}/K_{hh}) from 1 to 0.2 to force water outward from the drywell. • Added a 1.0-foot-wide Silty Clay CP layer around the primary and drywell chambers to restrict water movement and match as-built descriptions, then reduced saturated hydraulic conductivity from 6.57E-4 to 6.57E-8 to reduce permeability. Rationale is provided below.
Van Nuys Bioretention & Drywell	**Categories:** Boundary Conditions, Textural Class **Adjustments:** Saturated Hydraulic Conductivities, Specified Flow into Domain Boundary Conditions: • Varied "Specified Flow Into Domain (Q)" by recharge period. • Placed location of boundary conditions to allow for both vertical (z) and horizontal (r) inflow. Textural Class: • Added Silty Clay CP textural class with reduced saturated hydraulic conductivity (6.57E-4 to 6.57E-7) to model (8.5 ft to 18 ft) to significantly restrict vertical water movement and to reduce permeability. Rationale is provided below.

General Rationale Regarding Calibration Adjustments

- **Saturated Hydraulic Conductivity:** Adjustments were made to better represent site-specific soil permeability and effective flow behavior at the model scale to achieve alignment between simulated and observed infiltration. VS2DI requires parameter values that capture bulk system response, not just point-scale measurements. As a result, calibrated hydraulic conductivity values often differ significantly—sometimes by several orders of magnitude—from those obtained in field or laboratory tests (Healy & Essaid, 2012). This difference arises because factors such as small-scale variations in soil, preferential flow paths, soil layering, and uncertainties in boundary conditions are not fully captured in measured values but must be accounted for in the model's effective parameters.

- **K_{zz}/K_{hh}:** Changes to anisotropy ratios accounted for directional flow tendencies in layered soils. Lowering anisotropy ratio (K_{zz}/K_{hh}) emphasized horizontal spreading where stratigraphy limited vertical movement, while maintaining higher ratios supported vertical infiltration in permeable zones.

- **Boundary Conditions:** Modifications ensured that water entry points and the movement of water through the profile accurately reflected real-world conditions during synthetic storm events. Adjustments to specified flux, total head, and inflow orientation allowed the model to reproduce observed recharge behavior under varying storm intensities and chamber configurations.

8.5.4 Sensitivity Analysis Summaries and Rationale

Rosemead Bioswale

Calibration of the Rosemead Bioswale infiltration model focused on adjusting the saturated hydraulic conductivities of textural classes to align simulated infiltration behavior with field observations. The most significant changes involved the sandy loam and loamy sand CP layers. The saturated hydraulic conductivity of the sandy loam was reduced by half (from 9.56×10^{-2} to 4.78×10^{-2} ft/hr), making this layer less conducive to vertical flow and thereby slowing the downward movement of the wetting front. In contrast, the loamy sand CP layer's conductivity was increased by an order of magnitude (from 4.78×10^{-1} to 4.78×10^{0} ft/hr), enhancing its ability to transmit water and facilitating more rapid infiltration through this coarser interval. These targeted adjustments were essential to reproduce the observed depth and timing of wetting front advancement during synthetic storm events. Sensitivity analysis indicates that the model's infiltration rates and moisture distribution are highly responsive to these conductivity values, with even moderate changes resulting in noticeable differences in simulated recharge. The calibration approach is consistent with standard vadose zone modeling practice, where effective conductivities are tuned within the plausible range for each soil class to reconcile model output with field data.

Headquarters Drywell

Calibration of the Headquarters Drywell infiltration model required substantial and coordinated adjustments to both boundary conditions and the hydraulic properties of several soil textural classes to accurately represent observed subsurface moisture dynamics during the recharge event. The saturated hydraulic conductivity of the sandy loam CP was reduced tenfold (from 1.45×10^{-1} to

1.45×10^{-2} ft/hr), and its anisotropy ratio (K_{zz}/K_{hh}) was lowered from 1.0 to 0.3, discouraging vertical movement and promoting lateral flow. Similar reductions in anisotropy (to 0.2) were applied to silt loam and silty clay loam, further steering water radially away from the drywell. A 1-foot-wide silty clay CP barrier was also introduced around the primary and drywell chambers, with its hydraulic conductivity reduced by four orders of magnitude (from 6.57×10^{-4} to 6.57×10^{-8} ft/hr), functioning as a localized vertical-flow barrier to restrict deep percolation immediately adjacent to the chambers and to mimic low-permeability backfill observed during construction. Boundary conditions, including specified flux and total head, were iteratively refined to stabilize recharge inputs and maintain realistic hydraulic gradients, ensuring that simulated wetting fronts matched neutron probe data at multiple depths and locations.

Collectively, these adjustments provided a physically consistent mechanism for controlling both the direction and magnitude of water movement around the drywell. The reduced conductivities and lower vertical-to-horizontal anisotropy in finer-grained materials suppressed vertical leakage, while the silty clay barrier further limited deep percolation near the chambers. This approach aligns with Darcy-based flow behavior under unit-gradient conditions and reflects the common field observation that vertical conductivity in layered soils is lower than horizontal.

Van Nuys Drywell

Calibration of the Van Nuys Drywell model required targeted adjustments to both boundary conditions and the hydraulic properties of a textural class to accurately reproduce observed infiltration and wetting front behavior. The most significant change was the introduction of a silty clay CP layer between 8.5- and 18-feet depth, with its saturated hydraulic conductivity (K_s) reduced by three orders of magnitude—from 6.57×10^{-4} to 6.57×10^{-7} ft/hr. This adjustment created a pronounced low-permeability horizon, reducing deep percolation capacity across the layer by a factor of 1,000 under unit-gradient conditions. This was essential to limit vertical infiltration and maintain a restrained wetting front, consistent with neutron probe observations in the borehole interval.

Boundary conditions were also carefully calibrated: the "Specified Flow Into Domain (Q)" was varied by recharge period to reflect event-based inflow, and boundary locations were set to allow both vertical (z) and horizontal (r) inflow, mirroring the mixed recharge pathways of the bioretention and drywell system. This approach aligns with VS2DI modeling guidance and ensures that event-dependent recharge is represented realistically while enforcing a vertical-flux limit at the base of the silty clay interval.

Collectively, these adjustments ensure that the model's deep percolation rates and wetting front advancement are highly sensitive to the assigned Ks value for the silty clay CP layer. The three-orders-of-magnitude reduction in Ks is within the documented variability for fine-textured soils and is physically justified by the need to reconcile boundary-driven inflows with the observed restriction of vertical water movement at depth. This calibration strategy leverages both the flexibility of VS2DI boundary condition assignment and the dominant control of low-permeability horizons in layered vadose zone systems

8.5.5 Summary of Calibrated Model Performance

VS2DI models were manually calibrated by adjusting soil texture classes and boundary conditions to align simulated infiltration depths with measurements from synthetic storm events. Calibration was considered complete when the simulated infiltration depths closely matched the observed data for each event. Once calibrated, these models were used to estimate deep percolation rates for each LID, as detailed in Section 9.

Table 16.—Model infiltration depths, widths, and performance summary

LID Name	Model Infiltration Depths and Widths	Calibration Target Achievement Summary[1]
Rosemead Bioswale	Synthetic Storm Event 1: @ 7.4 hours, y = 6.5 feet. Synthetic Storm Event 2: @ 4.5 hours, y = 6.5 feet.	The calibrated models for both synthetic storm events show water infiltrating to the target depths at the target times.
Headquarters Drywell	NP1: @ 4.7 hrs: Infiltration depth of y = 19.5 @ x = 121. NP2: @ 2.5 hrs: Infiltration depth of y = 19.5 @ x = 83.5; Infiltration depth of y = 23.0 @ x = 83.5. @ 6.6 hrs: Infiltration depth of y = 56.0 @ x = 81.0; Infiltration depth of y = 59.0 @ x = 83.5. NP3: @ 2.5 hrs: Infiltration depth of y = 49.0 @ x = 91.5; Infiltration depth of y = 78.0 @ x = 98.5.	At 2.5 and 6.6 hours after the model run began, infiltration targets were met. Some targets were met slightly before the target times and do not affect model calibration. At 4.7 hours after the model run began, infiltration is 1.0 foot away from the NP1 target of x = 122 and y = 19.5. The target is met in the model, however, at 5.1 hours after the run began. Due to the number of assumptions that were required for this modeling effort, and that all other calibration targets were met for this site, the model is considered calibrated.
Van Nuys Drywell	Upper infiltration depth: @ 2.3 hours, z = 18.0 feet Lower infiltration depth: @ 2.3 hours, z = 48.5 feet. Radial infiltration width: @ 2.3 hours, r = 10.5 feet.	The calibrated model after 2.3 hours shows water infiltrating to the target depths.

[1]No quantitative error metrics were computed as part of this assessment.

Limitation Regarding Quantitative Model Performance Metrics:
The calibration presented here is qualitative in nature, relying on matching simulated wetting front

arrival times and depths to discrete neutron probe observations. Standard quantitative performance metrics such as Nash-Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), or R^2 were not computed, as calibration targets were defined as binary threshold crossings rather than continuous time-series comparisons. As a result, the deep percolation rate estimates derived from these models should be regarded as order-of-magnitude approximations, subject to substantial parametric and structural uncertainty. Users should interpret these results with caution, recognizing that the absence of formal goodness-of-fit statistics limits the ability to rigorously quantify model predictive performance.

9. Deep Percolation Rates

This section describes how data from the VS2DI model were utilized to calculate deep percolation rates. Deep percolation rates presented here represent the downward movement of water below the root zone. Actual groundwater recharge may be less, depending on site-specific subsurface conditions.

9.1 Deep Percolation Rate Development

Observation points were established in each model at the commencement of deep percolation, which varied by model. These points were assigned numerical identifiers by the model, with nodes exhibiting negative percolation rates excluded from consideration. Vertical velocity data were recorded at 30-minute intervals during simulated synthetic storm events and subsequently plotted to identify consistent slopes across observation points. Figures 26-30 represents vertical velocity measurements at a specific depth within the model domain. That is, every series corresponds to an observation node located at a distinct depth, allowing for the comparison of percolation rates at different vertical positions. The figures are designed to show how vertical velocities vary with depth over the course of the simulated storm event. In some instances, certain observations produced identical results, leading to overlap within the figures. In the following figures, the series labels (e.g., 1283, 1284, 1285…) correspond to VS2DI observation point identification numbers and do not represent units.

Rosemead Bioswale

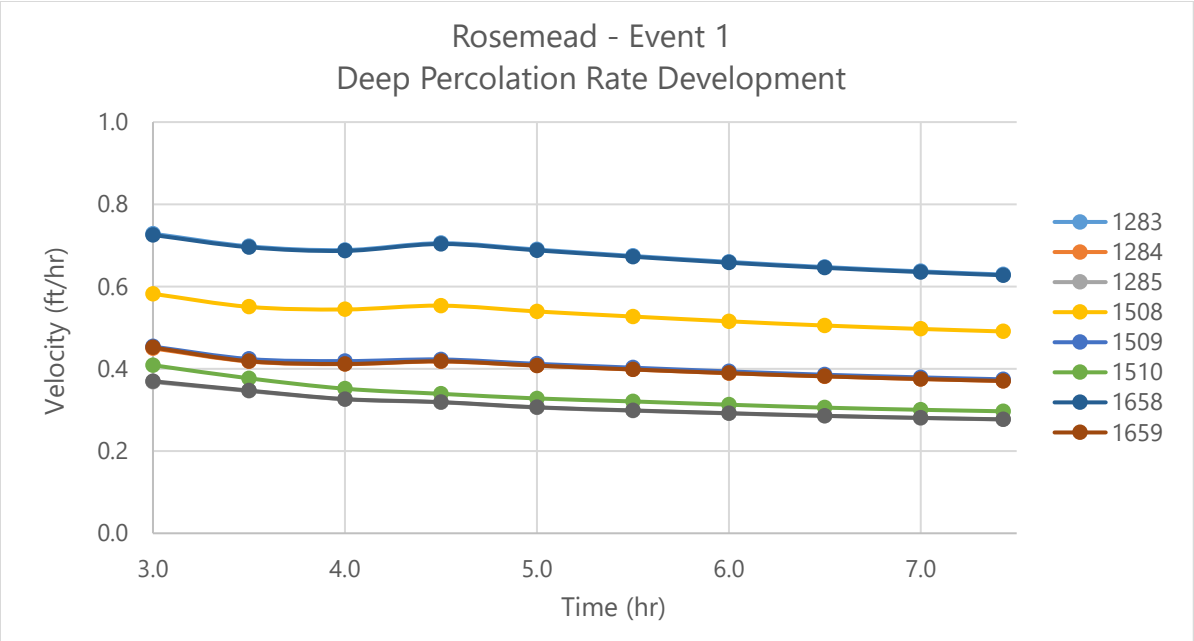

Figure 26.—Rosemead Bioswale deep percolation rate development for Synthetic Storm Event 1.

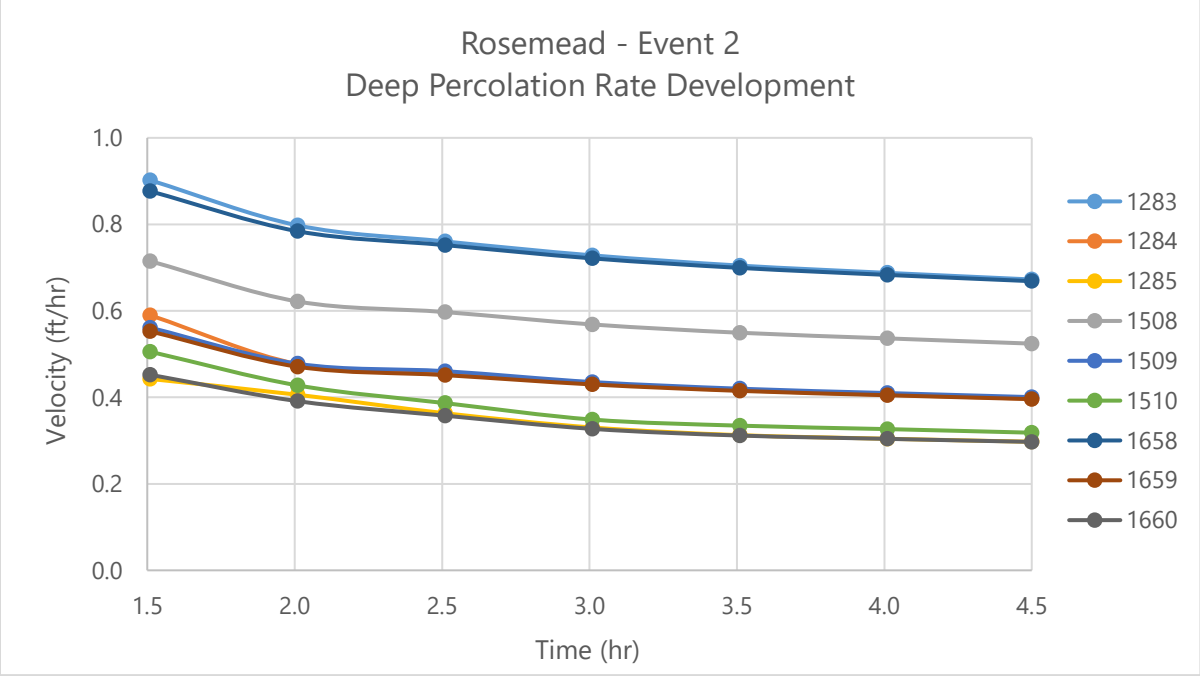

Figure 27.—Rosemead Bioswale deep percolation rate development for Synthetic Storm Event 2.

Headquarters Drywell

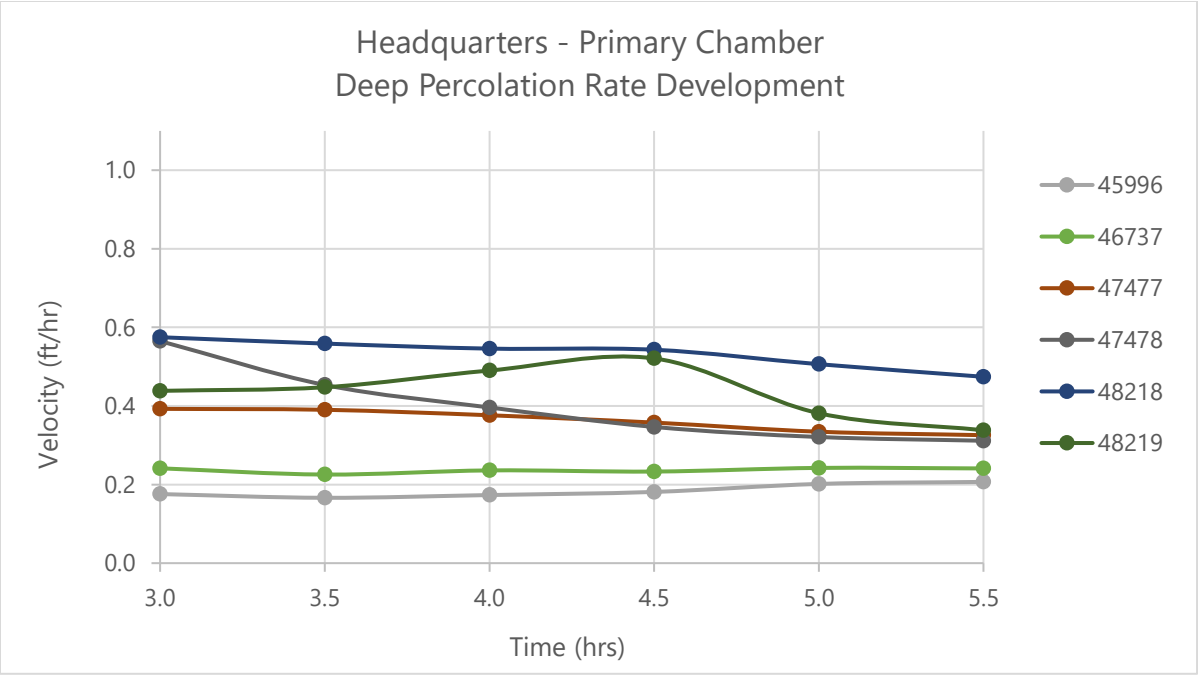

Figure 28.—Headquarters Drywell primary chamber deep percolation rate development.

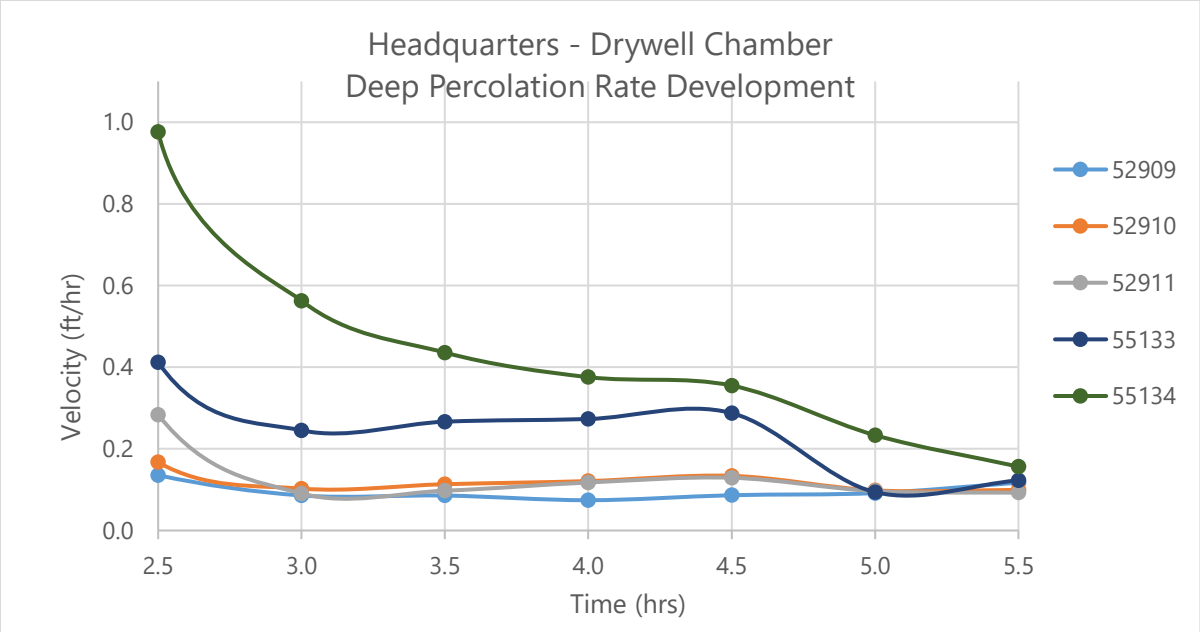

Figure 29.—Headquarters Drywell chamber deep percolation rate development.

Deep percolation rates at the drywell were excluded, as results showed that infiltration during the synthetic event was mainly lateral and vertical, with little downward movement.

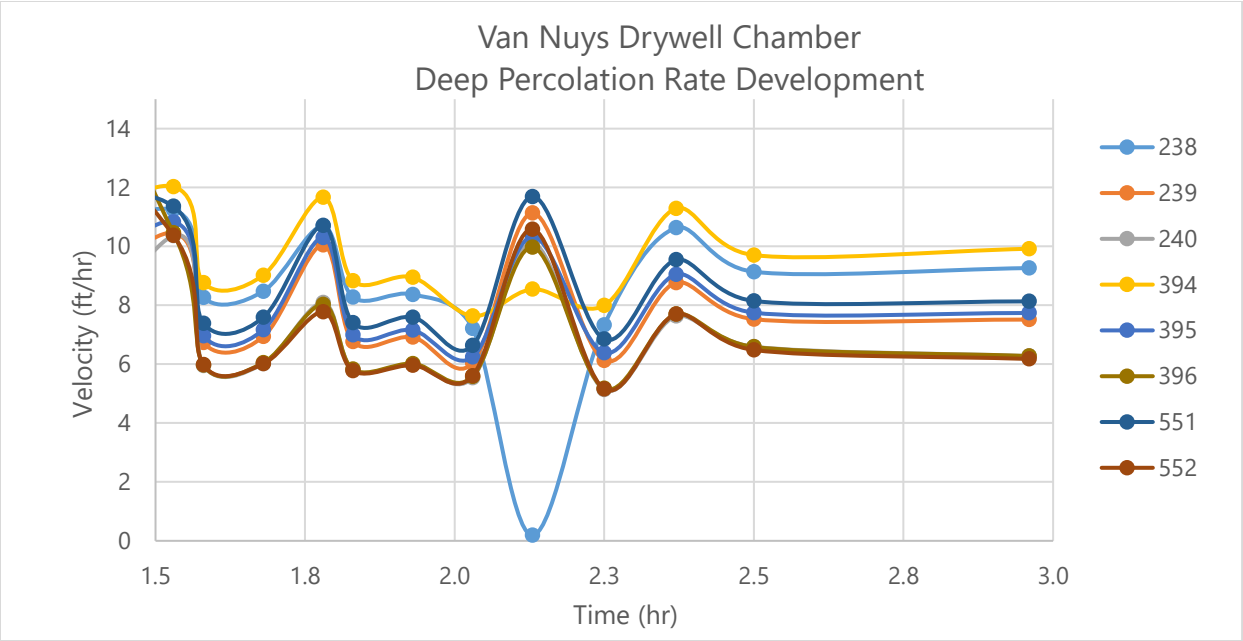

Figure 30.—Van Nuys Drywell chamber deep percolation rate development for Synthetic Storm Event 1.

9.2 Deep Percolation Rate Results

Deep percolation rates were determined by averaging vertical velocities of the nodes in Figures 26-30 over the specified time periods. Table 17 summarizes these rates for each LID.

Table 17.—Model time periods and corresponding deep percolation rates by LID

LID Name	Model Time Period (hr)	Deep Percolation Rate (ft/hr)
Rosemead Bioswale	Event 1: 3.0 – 7.5 Event 2: 1.5 – 4.5	0.4 0.5
Headquarters Drywell	Primary Chamber: 3.0 – 5.5 Drywell Chamber: 2.5 – 5.5	0.4 0.2
Van Nuys Bioretention & Drywell.	Drywell Chamber: 1.5 – 3.0	8.3

9.3 Site Comparisons and Observations

The three monitored Low Impact Development (LID) sites—Rosemead Bioswale, Headquarters Drywell, and Van Nuys Drywell—exhibited distinct infiltration behaviors due to differences in design, subsurface conditions, and synthetic storm event volumes and durations.

The model's soil moisture and saturation outputs provide insight into temporary water storage and the timing of recharge, which are key to evaluating the full recharge potential of LID features. These represent idealized estimates and using them for annual recharge requires assumptions about storm frequency, event duration and distribution, antecedent moisture, and long-term maintenance of LID inlet conditions, none of which were included in this analysis.

Rosemead Bioswale

Shallow infiltration dominated, with wetting fronts largely confined to the upper 6.5 feet during synthetic storm events. Deep percolation rates were modest (0.4–0.5 ft/hr), reflecting limited vertical movement beyond shallow horizons. Observations suggest bioswales are effective for near-surface soil moisture enhancement but may provide limited direct recharge to deep aquifers without favorable subsurface conditions.

Headquarters Drywell

Infiltration extended to depths exceeding 70 feet, indicating strong vertical connectivity through engineered chambers. Deep percolation rates were moderate (0.2–0.4 ft/hr), with delayed wetting at deeper horizons suggesting gradual migration through layered soils.

Van Nuys Drywell

The Van Nuys drywell exhibited the highest deep percolation rate among the study sites, with a modeled rate of 8.3 ft/hr and rapid infiltration to depths exceeding 40 feet within hours. This elevated rate is attributed to the presence of a highly permeable gravel segment at depth, as indicated by a pronounced wetting response at 42.7 ft (Neutron Probe 1), while no infiltration was observed in the upper 0–19.7 ft due to a modeled low-permeability barrier. The reliability of this high rate depends on the sustained presence and continuity of the deep gravel layer; if the hydraulic conductivity of this layer were lower or if the gravel were discontinuous, the actual deep percolation rate could be substantially reduced, and the wetting response at depth would be delayed or diminished. Thus, while the model matches the observed data and stratigraphy, the reported rate should be interpreted as an upper bound for conditions where a continuous, highly permeable gravel layer is present, and lower rates are plausible under less favorable subsurface conditions. This underscores the importance of soil permeability, engineered design, and careful site characterization when interpreting results and applying them to planning or design.

9.4 Study Limitations

The model results presented in this study are subject to several important limitations. First, there is significant uncertainty in the hydraulic properties assigned to each soil layer, as field and laboratory measurements often differ from the effective values required for model calibration. The use of

interpolated or literature-based parameters, particularly for deeper or less-characterized layers, introduces additional uncertainty (Döll & Flörke, 2005). Boundary conditions were developed from observed synthetic storm events but may not fully represent the variability of natural storms or inflow dynamics. The two-dimensional (2D) modeling approach captures vertical and lateral flow along a representative cross-section, but cannot account for three-dimensional heterogeneity, preferential flow paths, or complex site geometries. At the Headquarters Drywell site, a sustained decrease in volumetric water content (θ) was observed at a depth of 6.6 feet in Probe 3 during the synthetic storm event. This response is unusual for infiltration monitoring and may be attributed to probe malfunction, stratigraphic variation, or anomalous pre-event moisture conditions. Consequently, this data point was omitted from model calibration, and its exclusion introduces some uncertainty in interpreting wetting front progression at this location. For the Rosemead Bioswale, the long interval between synthetic storm events introduces additional uncertainty. Although no visible changes in site conditions were noted, the absence of maintenance records means that unobserved factors—such as vegetation growth, sediment accumulation, or soil compaction—as well as differing antecedent moisture conditions, may have affected infiltration rates. These factors should be considered when interpreting differences between the two events.

The study's focus on short-term synthetic events means that longer-term processes—such as seasonal groundwater mounding, antecedent soil moisture, and cumulative recharge—are not directly simulated. Deep percolation rates below the instrumented depth are inferred from model output rather than direct measurement, and calibration is constrained by the spatial and temporal resolution of neutron probe data. Extrapolation of site-scale results to larger areas or annual recharge estimates requires assumptions about the frequency, distribution, and maintenance of LID features, as well as the uniformity of subsurface conditions.

As a result, the reported deep percolation rates and recharge volumes should be interpreted as best estimates under the specific conditions modeled, and not as precise predictions for all potential scenarios or locations. Future studies could reduce uncertainty by incorporating additional field measurements, longer-term monitoring, and three-dimensional modeling approaches.

10. Limitations and Uncertainty

This study's modeling results and deep percolation rate estimates are subject to several important limitations and sources of uncertainty. While many of these are discussed in context throughout the report, they are consolidated here for clarity:

a. **Qualitative Calibration and Lack of Independent Validation:**
   The calibration of the infiltration models is qualitative, based on matching simulated wetting front arrival times and depths to discrete neutron probe observations. Standard quantitative performance metrics (e.g., Nash-Sutcliffe Efficiency, RMSE, R^2) were not computed, as calibration targets were defined as binary threshold crossings rather than continuous time-series comparisons. No independent validation dataset was available. As a result, the deep percolation rate estimates should be regarded as order-of-magnitude approximations subject to substantial parametric uncertainty.

b. **Reliance on Single Synthetic Storm Events:**
For two of the three study sites (Headquarters Drywell and Van Nuys Drywell), model calibration and deep percolation estimates are based on a single synthetic storm event. This limits the ability to assess model robustness under varying antecedent moisture, storm intensity, or maintenance conditions.

c. **Parameter Non-Uniqueness and Hydraulic Conductivity Adjustments:**
Model calibration required orders-of-magnitude adjustments to saturated hydraulic conductivity values relative to laboratory or field measurements. This reflects the need to account for bulk system behavior and unresolved heterogeneity but also implies significant parameter non-uniqueness and uncertainty in the physical representativeness of the calibrated values.

d. **Geometric Simplification at Headquarters Drywell:**
The Headquarters Drywell was modeled using a 2D Cartesian coordinate system, which treats the cylindrical chambers as infinite line sources rather than true cylinders. This geometric simplification may affect computed flux distributions and deep percolation estimates, and should be considered when interpreting results (see Section 8.4.3)

e. **Projection of Off-Plane Neutron Probes and Spatial Uncertainty:**
At the Headquarters site, neutron probe access tubes (especially NP3) were not aligned with the model plane. Their measured radial distances were projected onto the 2D model plane, introducing spatial uncertainty in the interpretation of wetting front arrival and infiltration dynamics at those locations (see Section 8.4.3).

These limitations, together with additional sources of uncertainty discussed in Section 9.4, should be considered when interpreting the results of this study and applying them to planning or design.

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Appendix A

A1. Literature Review

A1.1 Water Augmentation Study (WAS)

Year Published: 2010

Study Objective: The Water Augmentation Study (WAS), conducted by the Los Angeles and San Gabriel Rivers Watershed Council and completed in January 2010, evaluated the feasibility and benefits of decentralized stormwater management practices—particularly Low Impact Development (LID)—to enhance infiltration in the Los Angeles region (Los Angeles & San Gabriel Rivers Watershed Council, 2010). The study provided strategies and recommendations to maximize the effectiveness of decentralized approaches. As part of the study, surface and subsurface water quality monitoring was conducted at six sites retrofitted with various infiltration structures, including landscaped swales, catch basins, dry wells, and infiltration galleries. Monitoring occurred during the 2003–2004 and 2004–2005 storm seasons, with some sites also monitored in earlier years.

To support the WAS, Reclamation developed the Groundwater Augmentation Model (GWAM) to estimate stormwater runoff and recharge potential. The model assumed that all water percolating below the root zone would contribute to deep percolation.

Key Findings:

- Infiltrating the first ¾" of rainfall on each parcel by using LIDs could increase groundwater recharge in the region from 16% of annual rainfall to 48%.
- Results showed no clear evidence that stormwater infiltration adversely affected groundwater quality.
- GWAM estimated that decentralized stormwater management could contribute approximately 384,000 acre-feet (af) of groundwater recharge annually.
- While the study recommended further research to better understand the effects of decentralized stormwater management on groundwater levels, it did not evaluate how much of the recharge would be available for water supply.

Relevance to this Study: Evaluated the feasibility of Low Impact Development in the LA Region.

A1.2 Stormwater Recharge Feasibility and Pilot Project Development Study

Year Published: 2012

Study Objective: Conducted by the Council for Watershed Health, Geosyntec Consultants, and the Santa Monica Bay Restoration Commission for the Water Replenishment District (WRD) of Southern California, this study evaluated the feasibility of implementing distributed stormwater recharge projects within WRD's 420 square-mile service area in Los Angeles (WRD of Southern California, 2012). The study built upon findings from the Water Augmentation Study by identifying the most suitable locations for stormwater capture projects that could enhance drinking water supply and provide additional benefits through infiltration-based methods.

Key Findings:

- 17,000 af/yr of infiltration from distributed Best Management Practices in the identified feasible locations could be infiltrated in the WAS study area.

Relevance to this Study: Identified stormwater infiltration quantity as well as suitable locations for stormwater capture projects in the LA region.

A1.3 LA Department of Water and Power: Stormwater Capture Master Plan (SCMP)

Date Published: August 2015

Objective: Developed as part of the LA Basin Study, the plan outlines potential strategies for implementing stormwater capture and watershed management programs in the City of Los Angeles (LADWP, 2015).

The SCMP utilized the Load Simulation Program in C++ (LSPC) and the Groundwater Augmentation Model (GWAM) model, both developed by the Bureau of Reclamation for the Water Augmentation Study, to estimate stormwater capture for both centralized and distributed stormwater projects. In this model, sub-basins were categorized into three groups based on their geological constraints and suitability for infiltration. Distributed projects were further classified as either direct use or infiltration. The types of distributed infiltration projects included in the SCMP are rain gardens, dry wells, and permeable pavement.

Key Findings:

- Simulation modeling for the SCMP indicated that out of approximately 63,000 acre-feet per year (af/yr) of stormwater infiltrating from permeable areas throughout the city, only 35,000 af/yr (56%) contributed to recharging water supply aquifers.
- The remaining 28,000 af/yr (44%) infiltrated into soils above confined aquifers.
- Conservative estimates for stormwater capture from distributed infiltration projects ranged from 5,000 af/yr in 2020 to 31,000 af/yr in 2035.
- More aggressive estimates suggested a range of 11,000 af/yr in 2020 to 56,000 af/yr in 2035.

Relevance to this Study: A precursor to the LA LID Study that provided estimates of recharge volumes below LID types.

A1.4 LA Sustainable Water Project: Los Angeles City-Wide Overview

Year Published: 2018

Study Objective: Completed by the Institute of the Environment and Sustainability at UCLA, the Sustainable LA Grand Challenge, and Colorado School of Mines (Mika et al., 2018), the study evaluated Low Impact Development (LID) and modeled water quality impacts using the EPA's SUSTAIN model. The study assessed both treat-and-release and infiltration Best Management Practices (BMPs) as well as estimated the groundwater recharge potential for the Ballona Creek, Dominguez Channel, and LA River watersheds. The study also included water quality impacts of BMPs

Key Findings:

- Infiltration BMPs improve receiving water quality while also enhancing groundwater recharge.
- The study did not quantify how much of this recharge could be used for potable water supply.
- The study recommended to better quantify the water supply benefits of stormwater infiltration using integrated surface and groundwater models for all of LA.

Relevance to this Study: Regional study that estimated groundwater recharge potential and water quality impacts of BMPs.

A1.5 Thematic Research Plan for Stormwater Best Management Practices (BMPs)

Published: May 2019

Objective: Developed by the Southern California Coastal Water Research Project (SCCWRP), the plan created a scientific foundation for understanding, designing, implementing, and optimizing stormwater Best Management Practices (BMPs) in Southern California (SCCWRP, 2019). The plan aims to support regulatory compliance, water quality improvement, and cost-effective watershed management by guiding research across the full lifecycle of BMPs—from pollutant source identification to receiving water impacts.

Key Elements:

- Created conceptual model framework
- Identified focus areas for BMP intervention, research priorities, developing tools, and developing data infrastructure.

Relevance to this Study: Local expertise and relevant context for implementing understanding, designing, and implementing BMPs in Southern California.

A1.6 LACPW Low Impact Development Standards Manual

Year Published: 2014

Objective: Developed by Los Angeles County Public Works, the manual provides comprehensive guidelines for designing various types of LIDs (Los Angeles County Public Works (LACPW), 2014). The manual also identified standards for an LID site to be effective, including being directly connected to an accessible aquifer.

Key Elements:

- Established geotechnical parameters to assess the suitability of LID sites
- Identified focus areas for BMP intervention, research priorities, developing tools, and developing data infrastructure.
- Identified other parameters for BMPs to be effective.
- Outlined the procedures for stormwater management:
    - For utilizing programs developed by LACPW to calculate the project site required stormwater retention volume.
    - Defined the stormwater capture volume as the greater of the following two criteria: 1) 3/4 inches for a 24-hour rain event, or 2) the 85th percentile of the 24-hour rain event, as determined from the Los Angeles County 85th percentile precipitation isohyetal map.
- Specific tasks outlined in the WAS were also included.

Relevance to this Study: Includes design standards for BMPs and stormwater management strategies in Los Angeles County.

A1.7 Other Local Papers and Studies

Stormwater Capture Potential in Urban and Suburban California (Garrison et al., 2014)

Year Published: 2014

Study Objective: Stormwater capture potential in urban and suburban California.

Key Findings:

- A one-inch rain event in Los Angeles County can generate approximately 30,000 acre-feet of stormwater runoff.
- Most runoff ultimately discharges into the Pacific Ocean.

Relevance to this Study: Potential stormwater capture and runoff volume.

A1.8 Non-Local Recharge Papers and Studies

Decentralized Groundwater Recharge Systems Using Roofwater and Stormwater Runoff (Stephens et al., 2011)

Year Published: 2011

Study Objective: Evaluate the effectiveness of stormwater capture for groundwater recharge in urban areas—particularly in arid climates—by assessing the performance of retention basins and low-impact development (LID) technologies, and to explore the viability of decentralized recharge systems as alternatives to regional infrastructure.

Key Findings:

- Field and modeling studies in New Mexico indicate that stormwater diverted to retention basins may recharge about 50% of precipitation that falls on the developed area, even in dry climates.
- Comparable volumes of recharge may be expected at homes, subdivisions, or commercial properties with low-impact development (LID) technologies for stormwater control that promote recharge over evapotranspiration.
- Groundwater quality has not been significantly impacted at sites that have been recharging stormwater to aquifers for decades.
- Distributed recharge systems may be a good alternative to centralized regional facilities where there is limited land for constructing spreading basins or little funding for new infrastructure.

Relevance to this Study: Stormwater capture for groundwater recharge in urban areas can be highly effective even in arid climates. Decentralized systems offer a viable alternative to large regional facilities, with minimal impact on groundwater quality over time.

Analyzing Low Impact Development Strategies Using Continuous Fully Distributed Coupled Groundwater and Surface Water Models (Marchildon & Kassenaar, 2013)

Year Published: 2013

Study Objective: Coupled SWMM with the Groundwater-surface Water Flow (GSFLOW) model to compare standard developments with LID impact mitigation strategies.

Key Findings:

- The results indicated that the implementation of cumulative LID measures reduced overall groundwater drawdowns by 86%, restored groundwater discharge to streams by 42%, and decreased runoff generation by 80%.
- This demonstrated substantial improvements to the hydrological system due to the application of LID strategies.

Relevance to this Study: Coupled surface runoff models with groundwater infiltration models reduced overall groundwater drawdowns and improved the hydrologic system.

Urban recharge beneath low impact development and effects of climate variability and change (Newcomer et al., 2014)

Year Published: 2014

Study Objective: A groundwater recharge study utilized a HYDRUS-2D numerical model to estimate recharge rates, volumes, and efficiency beneath a Low Impact Development (LID) Best Management Practice (BMP) infiltration trench and an irrigated lawn. The researchers compared these findings with historical data and future recharge scenarios. In situ drainage observations were analyzed alongside calculations using the Darcy Method and the Water Budget Method.

Key Findings:

- The results from both the in-situ measurements and the HYDRUS-2D modeling were complementary, particularly in simulating historical and future recharge scenarios.
- The study emphasized the importance of in situ data for accurately estimating recharge under current conditions and highlighted the benefits of using LID BMPs for groundwater recharge.

Relevance to this Study: 2D groundwater recharge study that emphasized the importance of in situ data for estimating recharge.

Cumulative Effects of Low Impact Development on Watershed Hydrology in a Mixed Land-Cover System (Hoghooghi et al., 2018)

Year Published: 2018

Study Objective: A spatially explicit ecohydrological model known as Visualizing Ecosystems for Land Management Assessments (VELMA) was employed to compare changes in watershed hydrologic responses before and after implementation of LID practices. The study examined various spatial configurations of LID scenarios.

Key Findings:

- Results concluded there were overall increases in shallow subsurface runoff and infiltration, as well as evapotranspiration.

- The study also found decreases in peak flows and surface runoff across all types and configurations of LID practices.
- Among individual LID practices, rain gardens had the highest implementation level of substantial changes to the overall watershed hydrology, although the effectiveness of LID practices was limited in mixed land cover watersheds.

Relevance to this Study: Implementation of some LID types yielded greater infiltration, namely the use of rain gardens.

Low-Impact Development Effects on Aquifer Recharge Using Coupled Surface and Groundwater Models (Mooers et al., 2018)

Year Published: 2018

Study Objective: Assessed aquifer recharge by coupling PCSMWMM with MODFLOW to determine the potential effects on groundwater availability in a residential development area within a predominantly forested catchment.

Key Findings:

- The study suggested that LID practices could help restore predevelopment aquifer recharge conditions.

Relevance to this Study: Coupled surface runoff models with groundwater infiltration models to investigate restoration of predevelopment aquifer conditions.

Modeling the Spatial and Seasonal Variations of Groundwater Head in an Urbanized Area under Low Impact Development (Zheng et al., 2018)

Year Published: 2018

Study Objective: Coupled surface runoff models with groundwater infiltration models to estimate recharge using Low Impact Development (LID) technologies. The study examined the spatial and seasonal variations of groundwater head and hydrological responses under different LID scenarios. This was achieved by coupling the USEPA's Storm Water Management Model (SWMM) with the Finite Element Subsurface FLOW system (FEFLOW).

Key Findings:

- The findings revealed that annual surface runoff decreased by 5% to 9% compared to impervious areas when runoff was managed through LID facilities.
- The study concluded that LID significantly enhanced groundwater recharge and aquifer storage during wet seasons, which subsequently increased aquifer release and groundwater discharge in dry seasons.

Relevance to Study: Coupled surface runoff models with groundwater infiltration models to enhance recharge using Low Impact Development (LID) technologies.

A2. Previous Regional Modeling Tools

A2.1 Watershed Management Modeling System (WMMS)

Year Developed: 2021

Objective: The Los Angeles County Flood Control District developed the Watershed Management Modeling System (WMMS) tool to allow for simulation of all the major watersheds within Los Angeles County including hydrologic and pollutant generation processes, transport routines, and forecasts of benefits that could be achieved by stormwater capture infrastructure and source control programs (Los Angeles County, 2021).Version 1.0 was released in 2009 and was updated to Version 2.0 released in 2020. The WMMS configuration and calibration process includes the following:

3,117 square miles of model domain	2,500+ miles of explicitly modeled stream network
2,655 subwatersheds	662 precipitation nodes for weather boundary conditions
4,066 'jurisheds'	11 water reclamation plants
26 dams	26 spreading grounds
109 debris basins	23 stream diversions
34 hydrologic calibration stations	83 water quality calibration stations

Key Elements:

- WMMS is built upon two open-source models developed by USEPA, LSPC, and SUSTAIN.
- LSPC is a hydrologic model and SUSTAIN is a Best Management Practice, or BMP model.

Relevance to this Study: Local surface water runoff models developed for the LA Basin prior to this study. The WMMS models could be coupled with the models developed for this study.

A2.2 Loading Simulation Program in C++ (LSPC)

Year Published: 2021

Objective: The LSPC component of WMMS 2.0 is an open-source, process-based watershed modeling system developed by the U.S. Environmental Protection Agency (EPA) for simulating watershed hydrology, sediment erosion and transport, and water quality processes from both upland contributing areas and receiving streams (Shen, Jian, Andrew Parker, and John Riverson, 2005).

Key Elements:

- LSPC serves as the baseline watershed model within WMMS 2.0, and includes improved representation of land characteristics, meteorological boundary conditions, and pollutant sources and transport.
- The LSPC model was calibrated and validated based on extensive hydrologic and water quality monitoring datasets available throughout Los Angeles County watersheds.

Relevance to this Study: Developed to serve as a baseline watershed model for WMMS.

A2.3 System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN)

Year Published: 2009

Objective: The SUSTAIN component of WMMS 2.0 is an open-source, decision support system developed by the USEPA that provides process-based simulation and cost-optimization of BMPs (EPA, 2009b). WMMS 2.0 provides updates to SUSTAIN for model code generation and BMP cost estimation and creates a web-based user platform that was developed to enable maximum usability and transparency for LSPC and SUSTAIN applications in the County.

Key Elements:

- Platform includes:
    - A file repository where the LSPC and SUSTAIN executables and input data can be downloaded, an interactive map and timeseries viewer to illustrate LSPC model inputs and outputs.
    - A utility suite with support documentation to facilitate BMP cost optimizations that can inform watershed planning efforts.
- In concert, the updated LSPC baseline model, SUSTAIN model, and the WMMS 2.0 web platform provide a substantively more powerful and accessible modeling framework, further empowering successful stormwater management for LA County watersheds.

Relevance to this Study: Developed to provide updates to components of WMMS including model code, parameterization, and local cost estimation of BMPs.

A3. Monitoring Methodology

Geosyntec consultants

engineers | scientists | innovators

EVALUATING LOW IMPACT DEVELOPMENT (LID) AND GROUNDWATER INTERACTIONS

PHASE I

Prepared for

Los Angeles County Public Works

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9 January 2024

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1. INTRODUCTION

1.1 Project Background

Determining the effectiveness of various Best Management Practices (BMPs) on groundwater recharge rates is a key component in planning for the resilience of Los Angeles County's (LAC's) groundwater supply. Among numerous factors, subsurface conditions and rainfall patterns are critical to the effective groundwater recharge potential. The Los Angeles Basin Study (Basin Study) identified the improvement of LAC's stormwater infrastructure as critical to the resilience of regional water supply, especially when considering potential effects of climate change. However, the efficiency of several types of decentralized low impact development (LID) BMPs in infiltrating captured stormwater into underlying aquifers within the study area has not been thoroughly studied.

To better determine the water supply benefit achieved by LID BMPs, a subsurface evaluation of LID performance is needed. To improve LID understanding beyond design, LAC proposed instrumenting and monitoring selected LIDs at high resolution to estimate water movement into and out of the BMPs, with a particular focus on subsurface water movement between the BMP infrastructure and the surrounding soil. Additionally, datasets collected will be utilized for a new BMP modeling tool being developed in tandem by the Bureau of Reclamation (USBR). The data types collected include soil texture, moisture, and structure; water level and volume; and 4D geophysical monitoring at the selected locations within the Los Angeles region. This study helps to quantify shallow and deeper percolation rates using the field data and provides a visual understanding of the infiltrated water movement through the subsurface. This effort builds upon the earlier work by USBR on subsurface modeling and could interface with Los Angeles County's Watershed Management Modeling System (WMMS) or similar surface and subsurface infiltration models.

This study was first accepted by USBR in 2019, which has since been working cooperatively with Los Angeles County Public Works (LACPW). In addition to LACPW and USBR, the project team consists of Geosyntec Consultants (Geosyntec), Lawrence Berkeley National Laboratory (LBL), United States Geological Survey (USGS), and Los Angeles County Flood Control District (LACFCD). The team developed a field monitoring and sampling plan (Attachment 3) that described the process of field data collection. The approach consisted of using integrated geophysical imaging using time-lapse electrical resistivity tomography (ERTs) to define stratigraphic horizons to quantify water infiltration in a measured zone. This approach allowed the team to image water pathways in 2D and 3D, determine depths and distribution of water infiltration (when 3D), and to estimate the groundwater recharge rates and volumes that occur in stormwater LID BMPs in the Los Angeles region.

The study was designed as a two-phased approach: a pilot phase (Phase I) performed at two sites, and the development phase (Phase II) at additional sites and with additional instrumentation supplementing Phase I. The LID BMPs and selected locations are intended to represent common LID BMPs found throughout the region (e.g., bioswales and drywells). This report presents a summary of the pilot phase, Phase I, a controlled proof of concept which was primarily used to validate the monitoring design and provide book-end model parameter inputs to assess the USBR model prior to full-scale, long-term monitoring, in addition to best practices and lessons learned. Phase I was completed between August 2021 and May 2022. Phase II is expected to begin in Winter 2023/2024.

As part of the associated field activities, a combined monitoring Health and Safety Plan was developed to ensure safe monitoring and provide necessary information to field personnel during field drilling and monitoring execution. Geosyntec provided field oversight for the monitoring installation and related permitting with agencies. This included Geosyntec's identification and coordination with drillers for borehole development, as well as arrangements for traffic control, pavement cutting, laboratory testing, water meter rental, and drum disposal. LBL prepared geophysical instruments for installation, conducted field geophysical monitoring and data collection, and performed analysis and implementation of the geophysical modeling. Geosyntec and LBL provided multiple datasets to USBR for incorporation into the BMP model.

1.2 Project Design

The Phase I study collected data at two LID locations as follows:

a) A bioswale on Rosemead Boulevard, near the intersection of San Pasqual Street in East Pasadena, CA 91107. The bioswale is approximately 2.5 feet (ft) by 155 ft, with a drainage area of approximately 0.17 acres.

b) A drywell located at the parking lot of Los Angeles County Public Works (LACPW) Headquarters (HQ) building at 900 S Fremont Avenue, Alhambra, CA 91803. The drywell design drainage area is 1.72 acres and consists of a pretreatment well and main infiltration well, both 23.9 ft deep.

The Vicinity Map **(Figure 1)** shows the two LID BMPs investigated in Phase I. The LID BMPs and locations investigated in Phase I were selected to be representative of common LID BMPs utilized throughout Los Angeles County.

The Phase I study focused on simulating rainfall events by applying a known volume of water to each LID BMP via a fire hydrant at the two selected sites. The findings in Phase I provided valuable information towards the development of Phase II, which will include wet season monitoring at additional sites over a period of two years.

The project team initially proposed using a distribution of Cone Penetrometer Testing (CPT) to depth of groundwater to estimate subsurface hydraulic properties. However, this approach was based on an empirical correlation. No CPTs were completed, and this approach was modified with the methodology described in the following section. This change in approach to a more robust geophysical monitoring program resulted in significant increases to the project cost.

2. METHODOLOGY

Phase I consisted of collecting electrical resistivity tomography (ERT) time lapse data, soil moisture using point sensors and a neutron probe, and temperature data on the surface at each site. ERT data is acquired using numerous metal electrodes that are inserted into the ground along a borehole. Connecting these electrodes through a common cable permits the injection of current into the ground to generate an electrical field. The voltages across the electrical field are measured via the other electrodes in the ground, much akin to measuring the voltage on a battery with a voltmeter. Using multiple combinations from the dozens of electrodes generates voltage measurements related to soil electrical resistance associated with soil properties (texture, soil moisture, and fluid salinity) at various depths and can be used to estimate water

transmissivity. The acquired dataset is then processed with an inverse modelling technique to obtain representative images of the spatial distribution of the soil electrical resistivity and can be interpreted as water movement over time.

This ERT method was selected after determining the initial methodology using Cone Penetrometer Testing (CPT) would only allow for empirical data collection, which was insufficient to meet the data demands of the project. Because ERT is sensitive to soil texture, moisture content, and fluid salinity, it is a powerful and robust method for imaging and monitoring water infiltration since soil texture does not change over time. By collecting spatiotemporal soil moisture data with the neutron probe along each ERT borehole, it could be coupled with the temporal 3D ERT data to estimate soil moisture changes over time and space in addition to the distribution of soil texture. This provided a flexible approach to evaluate infiltration and to provide validation datasets to the USBR model.

2.1 Monitoring Well Development

In preparation for the ERT installation, two boreholes were advanced to 33.5 ft below ground surface (bgs) at the Rosemead Blvd bioswale, and three boreholes were advanced to 81.5 ft bgs at the LACPW HQ site. One soil boring was logged from each site to understand the subsurface materials with depth. **Table 1** and **Table 2** show the results from soil logging at each site, plus the laboratory analysis for each collected soil sample.

- On 25 August 2021, the boreholes at Rosemead Blvd bioswale site were drilled. The stratigraphy at this location generally exhibited fine grained sands and silts in the upper materials down to 11 ft bgs. Below 11 ft bgs, the stratigraphy indicated dry, well-graded sand and gravel between 11 ft bgs to 20 ft bgs, and deeper vadose zone materials were primarily silty sand and coarse-grained gravel between 20 ft bgs and 33.5 ft bgs. Moisture contents at the Rosemead Blvd site ranged from 1.9% to 4.5%.
- The boreholes at LACPW HQ site were drilled on 26 August 2021, and soil borings generally exhibited layers of sand and gravel in the upper 21.5 ft bgs. The stratigraphy at this location indicated fine-grained sands approximately between 25 to 61.5 ft bgs, and within the deep vadose zone, materials exhibited moist, silty and clayey sands between 65 to 81.5 ft bgs. Moisture contents at LACPW HQ were between 4.5% to 15%.

2.2 ERT and Geophysical Monitoring

ERTs were constructed by placing electrodes around a 2-inch PVC pipe within each borehole and backfilling the borehole with the soil cuttings and a series of bentonite plugs roughly spaced every 10 ft along each borehole. The top of each borehole was filled with approximately 2 to 3 ft of bentonite to stop any preferential flow along each borehole. Two and three ERTs were installed at the Rosemead and at the LACPW HQ site, respectively. This setup allowed the ERT survey to be collected in 2D at the Rosemead bioswale, and in 3D at the LACPW HQ drywell site.

ERT boreholes were instrumented with Hobo temperature pendants to record the temperature gradient down the borehole, along with the ERT electrodes attached at 1- to 3-foot intervals strapped to the outside of the piezometers at both sites. Distributed Temperature Probes (DTPs) monitored water infiltration using the diurnal heat flux incorporated into a 1D vertical infiltration model. The DTPs monitor the shallow subsurface in high resolution (sensors every 4 inches) down to 4 ft bgs at the Rosemead site. The high-resolution DTPs were used to estimate the near surface water flux using the phase lag of the peak

temperature at each sensor, and the Hobo temperature sensors were used to correct time-lapse ERT data because resistivity changes with temperature. Three METER soil moisture sensors were also installed in the top 3 ft of the soil profile, collocated with the DTP, to monitor shallow, engineered media changes in soil moisture due to synthetic and actual rain events. In addition, a METER water level sensor was installed to capture the water level over time at the Rosemead site. A salinity probe was installed to monitor the change in salinity of the flooding water to account for ERT correction that may be caused by salinity of the applied water at both sites. The shallow DTP and METER sensors were not used at the HQ site due to the presence of the asphalt parking lot.

Soil moisture along each ERT borehole at a spacing equal to the electrode spacing was collected temporally at each site, which included readings before, during, and after the controlled experiments. These high-resolution datasets were used to calibrate the ERT petrophysical transform used to estimate saturation from the ERT images and were also used to confirm where infiltration was happening around the BMPs. This suite of methods provided information on soil architecture, porosity, saturation, permeability, and infiltration rates, which are key data input parameters for USBR's hydrologic model. The site-specific ERT locations are described below.

2.2.1 Rosemead ERT Installation

Two, 4-inch boreholes were drilled for ERTs and monitoring equipment (**Figure 2**), approximately 18 ft apart and to a depth of 33.5 ft bgs. A temporary weir wall was installed to limit hydraulic connectivity between adjacent bioswale cells and the two curb cuts in the study cell were blocked off to prevent the applied water from flowing into the street. The ERT monitoring system consisted of 2-inch PVC pipe and sensors (ERTs) that were connected to the data logger box on the surface. Boreholes were backfilled with soil cuttings around the installed PVC pipe and sensors and finished with a well control box cover to allow easy access and protection of the wiring system. The ERT electrodes started at the ground surface and were installed at a frequency of one electrode every 1 ft, which resulted in 32 electrodes along each borehole (64 electrodes total) that were monitored continuously throughout the study. Soil moisture from neutron probe measurements were taken inside the cased ERT wells every 1 ft bgs to 33.5 ft bgs (1 m to 24 m). All cables were routed inside a length of PVC 1-inch pipe to the North end of the bioswale where an instrument cabinet would be installed at a later date for Phase 2 long-term monitoring. Shallow high-resolution sensors (DTP/METER) were also installed and described above.

2.2.2 LACPW Drywell ERT Installation

Three, 4-inch boreholes were drilled at the LACPW HQ drywell with a hollow-stem auger drill rig. Boreholes were approximately 25 to 35 ft apart (**Figure 3**). Similar to the ERT at the Rosemead location, the ERT monitoring system consisted of 2-inch PVC pipe and sensors. The ERT electrodes started at 16 ft bgs at this location and were installed at a frequency of one electrode every 3 ft. This design provided 24 electrodes per borehole and totaled 72 electrodes that were monitored continuously throughout the study. Soil moisture from neutron probe measurements were taken inside the cased ERT wells every 1.6 ft bgs to 78.7 ft bgs. Pressure sensors were also placed at this site in the pretreatment chamber and drywell to monitor water levels. Sensor wires were routed to a data logger box through a trench constructed between the monitoring wells (3 inches wide by 12 inches deep).

3. CONTROLLED EXPERIMENTS

The controlled experiments (CEs) were conducted at each LID monitoring site during Phase I in-lieu of a natural rain event because: 1) the installation occurred during the summer months; and 2) a known amount of water could be applied for a known amount of time, thus simulating a design storm event. This also allowed full knowledge of the water budget for the given event, thereby providing valuable data for the USBR model.

An ERT dataset was collected every 30 minutes at Rosemead and every 45-50 minutes at HQ during the duration of the simulated rain event. Each dataset consisted of over 1000 datapoints for each dataset at Rosemead and over 2500 datapoints for each dataset at HQ.

3.1 Rosemead Bioswale

The Rosemead Blvd bioswale CE was monitored from 30 August 2021, through 31 August 2021. Approximately 7,000 gallons of water were delivered to the bioswale over a period of 6 hours, with a constant head of 6 inches (15 cm) in the swale. Results were provided for 24 hours total, with the ERT and neutron probe capturing infiltration down to approximately 8 ft (2.5 m).

The data showed that water never reached deeper than 8 ft (2.5 m) bgs, despite maintaining a constant head during the CE. Surface drawdown occurred within the first hour after water stopped being supplied. **Figure 4** shows the soil moisture/water level and resistivity measurements from ERTs in the Rosemead bioswale during the CE. The resistivity image panels show the background (starting conditions) resistivity (red/green/blue colors) that highlight the soil structure beneath the bioswale. The yellow/red hotter colors indicate sandier soils compared to the cooler blue colors that indicate the more silty/clayey soils. On the right side of the panels the results from the soil logs are shown along ERT borehole 2 for comparison. Results from the neutron soil moisture monitoring (**Figure 5**) confirmed the changes observed in the time-lapse ERT images in **Figure 4**. Temporal increases in soil moisture are observed in both ERT boreholes down to 8 ft (2.5 m). Both boreholes increased in soil moisture from ~9% to 21%. Overall, the shallow infiltration of only 8 ft bgs suggests that water was moving laterally, possibly under the road, but further data collection is required to draw a conclusion.

3.2 LACPW HQ Drywell

The HQ drywell CE was monitored from 28 August 2021 through 30 August 2021. Approximately 26,000 gallons of water were delivered to the drywell over a period of 6 hours. ERT monitoring ran for 42 hours total. Monitoring included repeated ERT surveys and neutron probe soil moisture measurements.

Results from the time-lapse ERT are shown in **Figure 6**. The resistivity image panels show the background (starting conditions) resistivity (red/green/blue colors) that highlight the soil structure surrounding the drywell. The yellow/red hotter colors indicate sandier soils compared to the cooler blue colors that indicate the more silty/clayey soils. The location of the three ERT borings with the ERT electrodes are shown as a vertical array of grey spheres with the soil log overlain one of the vertical profiles. The pretreatment and primary containment structures are shown as darker grey cylinders extending to a depth of 24 ft, with the extension of the drywell as a transparent cylinder extending to a depth of 80 ft. Both the pretreatment and primary containment have perforations at the bottom of the concrete structure to allow for infiltration.

In the first ERT panel on the left (**Figure 6B**), water is observed exiting the bottom of the pretreatment as it fills to the overflow into the drywell. **Figure 6C** shows the applied water exfiltrating from 52.5 to 59 ft

(16 - 18 m). Additionally, infiltration is observed moving from the pretreatment horizontally within a sandy layer at 24 ft bgs, intercepting the primary containment and moving vertically down to 42.5 ft (13 m). **Figure 6D** shows the continued spatiotemporal movement of infiltrated water and in subsequent images (not shown) a decrease in the size of the volumes is observed, indicating water movement out of the monitored area. Results from the neutron soil moisture monitoring (**Figure 7**) confirmed the changes observed in the time-lapse ERT images in **Figure 6.** Temporal increases in soil moisture are observed in all ERT boreholes down to at the bottom of the containment units and the drywell. Interestingly, a greater increase in soil moisture along ERT-2 and ERT-3 is observed compared to ERT-1, which indicates the overall flow direction is toward the south. Both boreholes increased in soil moisture from ~11% to 21%. Drawdown in both wells was less than 30 minutes, indicating the subsurface could take more water before seeing an impact on infiltration.

Following the controlled experiment in late August 2021, the 2021-2022 wet season started early in December 2021 with multiple atmospheric rivers over the following four months. As part of the proof-of-concept, the monitoring ERT system was set to automatically collect data to assess the system during rain events while the team prepared for Phase 2. The preliminary result from this monitoring is further described in Section 5 below.

4. MODELING APPROACH

This study initially utilized the Green Infrastructure Flexible Model (GIFMod) from the United States Environmental Protection Agency (EPA), an open-source framework for modeling urban stormwater and agricultural green infrastructure (GI) practices. In GIFMod, models of various GIs were built as a combination of blocks representing different parameters including surface water depth, soil texture, streams, overland flow, saturated and unsaturated porous media, and storage volumes.

In addition to defining surface, subsurface, water quality and evapotranspiration variables, GIFMod can be further refined with other inputs including bulk density, moisture content, soil texture, soil electrical conductivity (EC), and saturated hydraulic conductivity, for example. These parameters were determined from soil analysis, and other soil hydraulic parameters such as EC were estimated from the geophysical data. These data were supplied to USBR as starting inputs for the GIFMod hydrologic model and were also used as calibration data at different time steps within the model.

Since completing Phase I, GIFMod has been replaced by OpenHydroQual, which is the next version of GIFMod. It has a more user-friendly interface and further transparency into the source coding. Therefore, the USBR team selected and is now using OpenHydroQual.

5. PERFORMANCE DURING A STORM SEASON

To further assess the field monitoring performance during this proof-of-concept phase, the ERTs at the LACPW HQ drywell continued the time-lapse data collection from December 2021 to March 2022 and transmitted to LBL for processing. **Figure 8** illustrates the performance of the LACPW drywell throughout actual storm events during the December 2021 – March 2022 period. In **Figure 8** at the start of the rain event water is observed exfiltrating from the primary chamber (~6 m depth) and drywell. Eight days later the majority of the water after the rain event is observed in the 12 – 16 m depth range. Indicating the shallower soils have drained and the system is at field capacity. **Figure 9** Shows another rain event highlighting the conditions before, during, and after the rain event. The downward water movement along

fast-paths is shown by the red arrow. The fast-path appears to link the water infiltrated by the primary chamber to the borehole drilled for the drywell. Other flow along the sandy sediments is observed. Days after the rain event the majority of the water appears to have moved away from the drywell and the system is ready for the next rain event.

6. CONCLUSIONS

6.1 Phase I Outcome

Given the importance of collecting data during the proof-of-concept phase, controlled water recharge scenarios were completed at two selected sites during Phase I. Storm event simulation was controlled by using a fire hydrant outfitted with a flow meter while monitoring the subsurface response to the synthetic rain event. In this way, the synthetic event applied known volumes and rates of water, allowing Phase I of the study to be less reliant upon installation of additional monitoring equipment (weather stations, flow control weirs, etc.) than the scaled-up phase (Phase II). In addition, these types of controlled studies allow the team to provide the most diverse datasets that can be used with USBR's hydrologic model that can be used as calibration points for the sensitivity analysis. This will ultimately provide insights regarding which data is the most important to have when using the modeling tool. Lastly, the controlled experiments offer a trove of lessons learned for monitoring BMPs in the short- and long-term. Overall, Phase I was successful at not only providing insights on how both BMPs functioned, but what type of data could be realistically captured in a longer-term study and how this data could be efficiently used for the hydrologic model being developed. These insights are paramount for the successful implementation of Phase II.

6.2 Phase II

Phase II will build upon the instrumentation, monitoring approach, lessons learned, and the successful ERT installation methods implemented in Phase I. Phase II will use the information gathered from the CEs completed at the Phase I sites to select new additional BMP sites, each site being equipped with five ERT monitoring boreholes. Two sites were initially selected for Phase II, which are located at Laurel Canyon Green Street near the intersection of Kagel Canyon Street, and the Van Nuys Blvd Green Street at the intersection of El Dorado Ave and Mercer St. After initial field investigations, only the Van Nuys site is a viable option for instrumentation, access, and monitoring. The Van Nuys site, located in the San Fernando Valley, has a variety of swale and drywell BMP combinations, allowing for monitoring of both BMP elements in combination with one another. Long-term seasonal monitoring will start following the controlled experiments at the new site.

The Phase II effort will also continue to evaluate the original Phase I sites at Rosemead and HQ. In addition, the Rosemead site will be expanded by adding two additional ERTs to determine if lateral flow is occurring under the road. Both initial sites will have long-term continuous monitoring and data analysis for up to two full years to assess performance under real environmental conditions.

ATTACHMENT 1

FIGURES



0 0.5 1 2 Miles

N

Legend

- Phase I Monitoring Sites

Los Angeles County Phase I LID Study

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Figure 1



0 25 50 100 Feet

N

Legend

- ERT Monitoring Wells
- Bioswale Boundary
- Surface Weir
- DataLoggerBox

Los Angeles County - Phase I
Rosemead Blvd Bioswale

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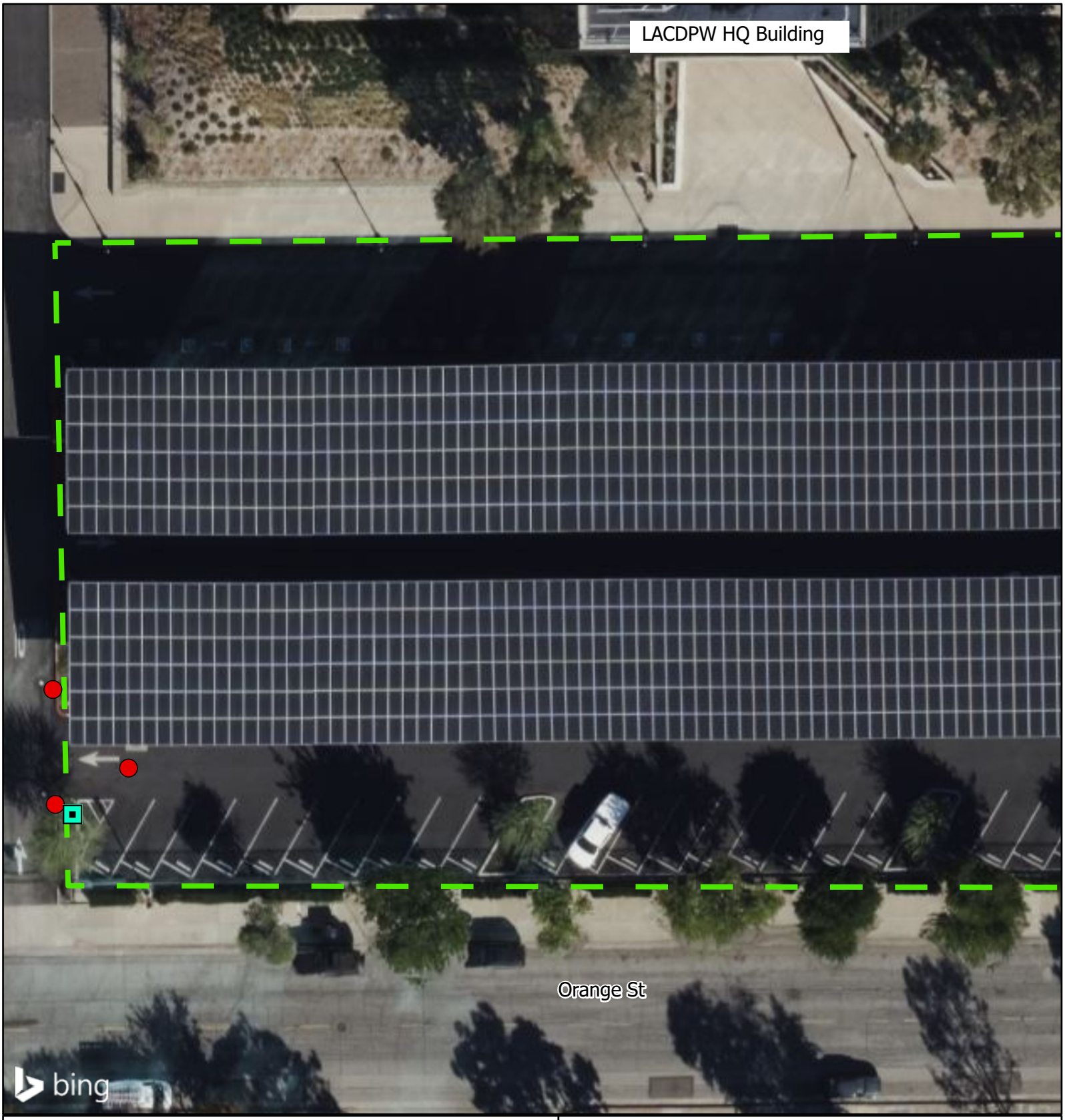
Figure 2



0 25 50 100 Feet

N

Legend

- ERT Monitoring Wells
- Data Logger Box
- Site Boundary

Los Angeles County - Phase I

LACDPW Parking Lot Drywell

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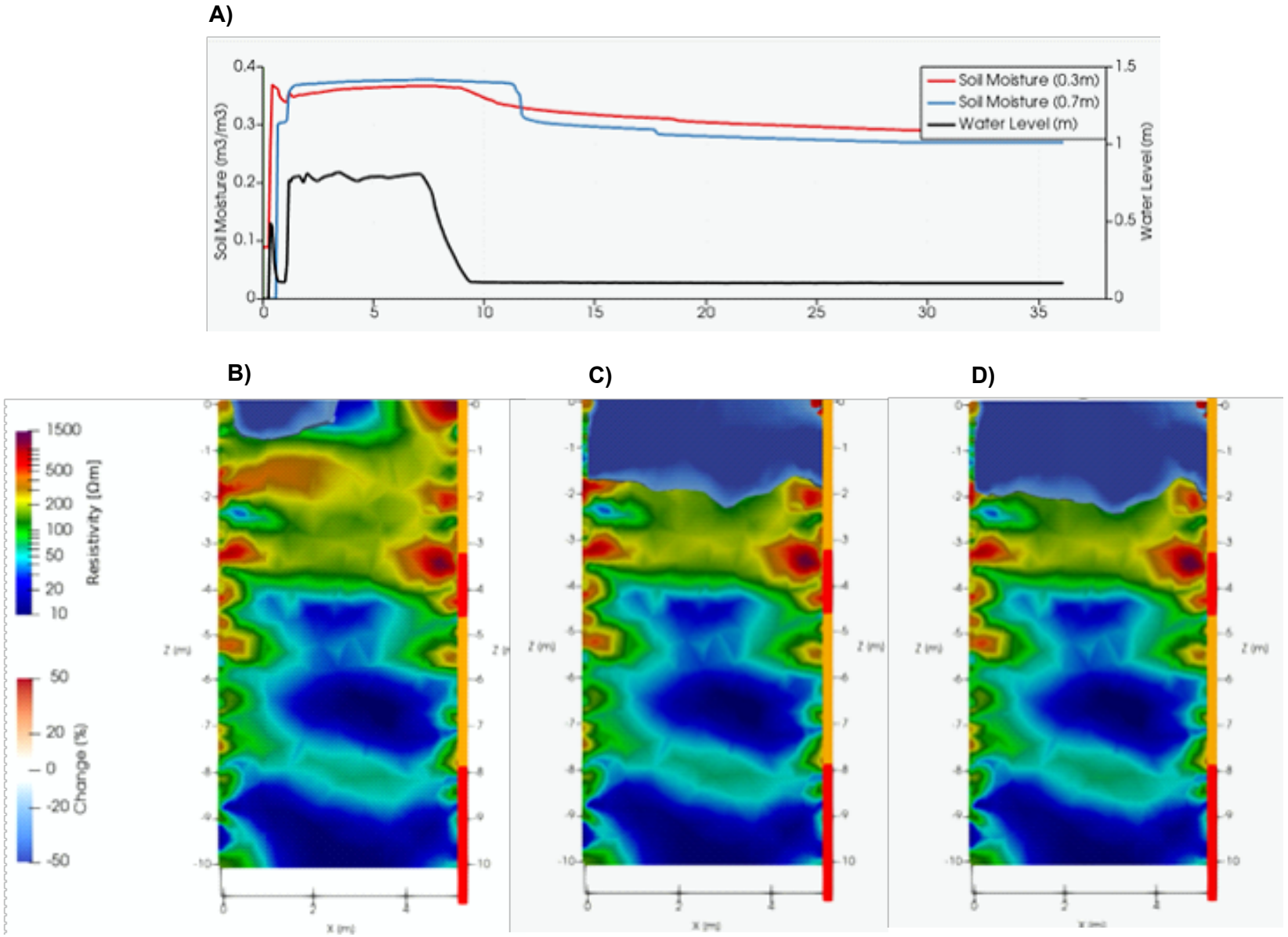
Figure 3



Top: A) Soil moisture at 0.3 m bgs and 0.7 bgs at the Rosemead bioswale monitoring site.

Bottom: ERT time-lapse data at Rosemead bioswale at **B)** 2 hrs, **C)** 5 hrs, and **D)** 24 hrs of applied water.

Los Angeles County - Phase I LID Study

ERT Time-lapse Results

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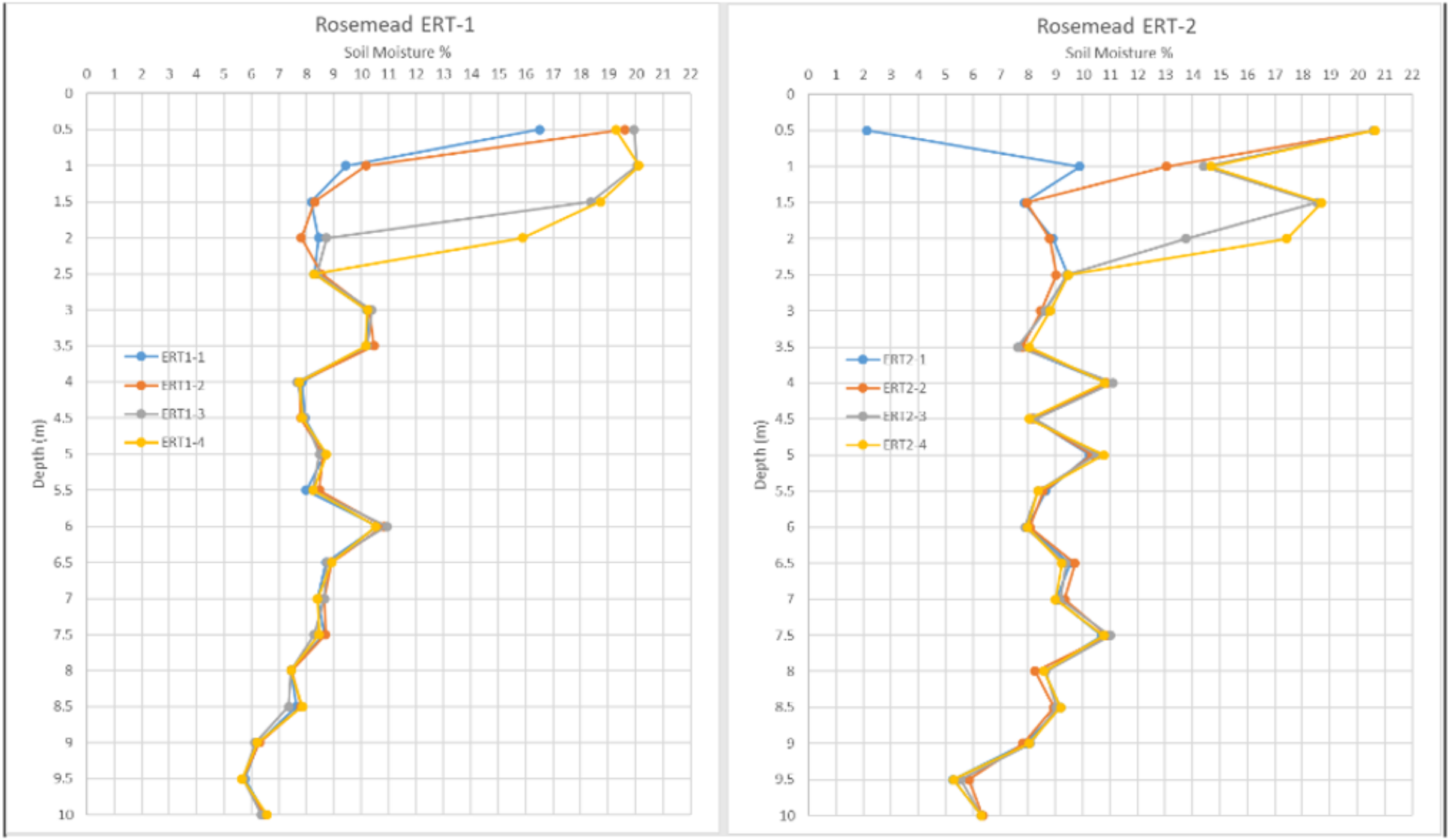
Figure 4



Notes: Time-lapse neutron probe curves at the Rosemead site in ERT boreholes 1 (left), and 2 (right). Both wells show an increase in soil moisture from the ground surface down to approximately 8 ft (2.4 m) and stopping.

Phase I LID Study

Rosemead Soil Moisture Curves

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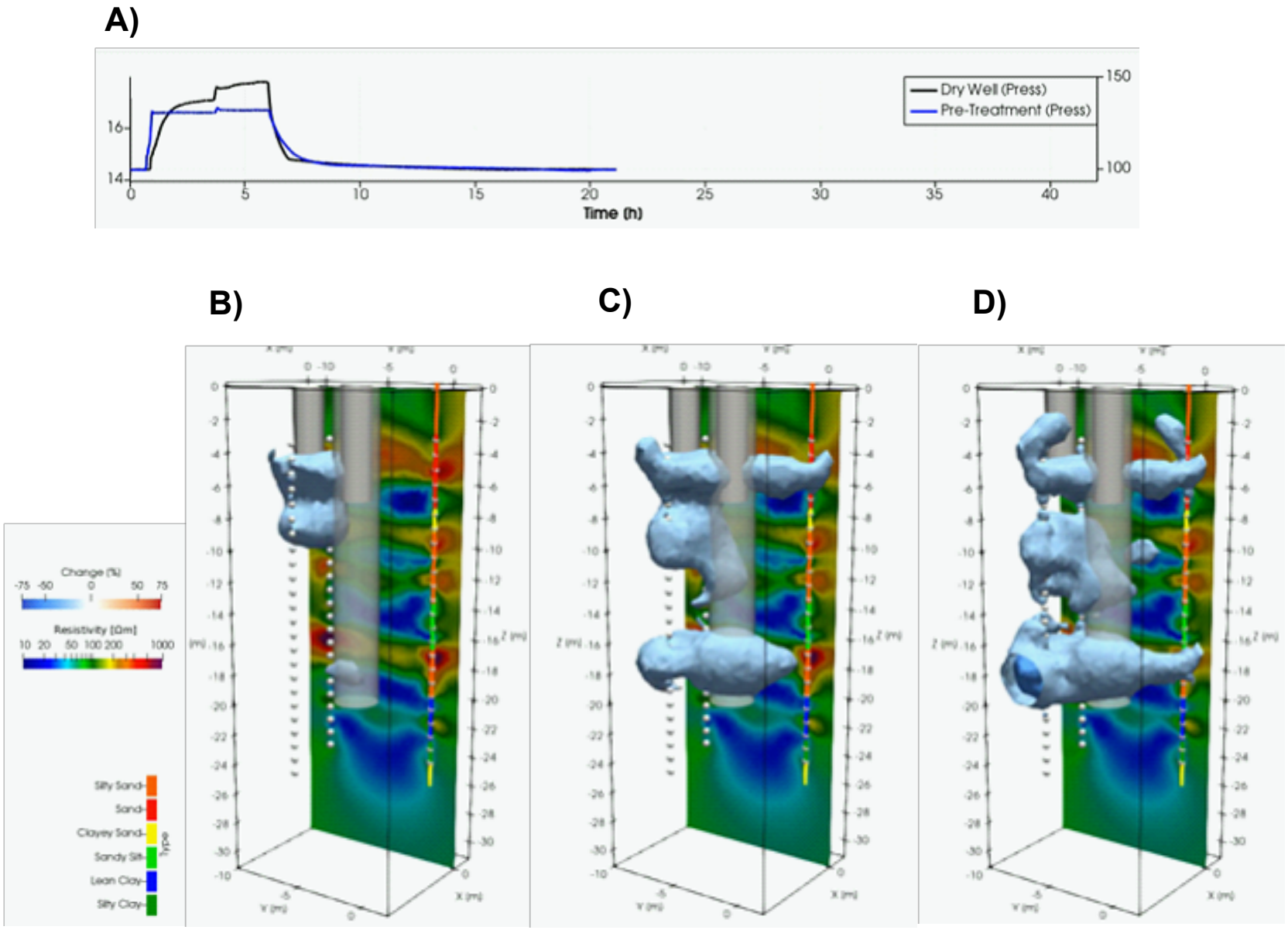
Figure 5



Top: A) Soil moisture in the drywell (black) and pre-treatment chamber (blue) of the LACPW Drywell.

Bottom: Time-lapse ERT data in 3-D at LACPW parking lot drywell at **B)** 2 hrs, **C)** 5 hrs, and **D)** 22 hrs.

Phase I LID Study

ERT Time-lapse Results

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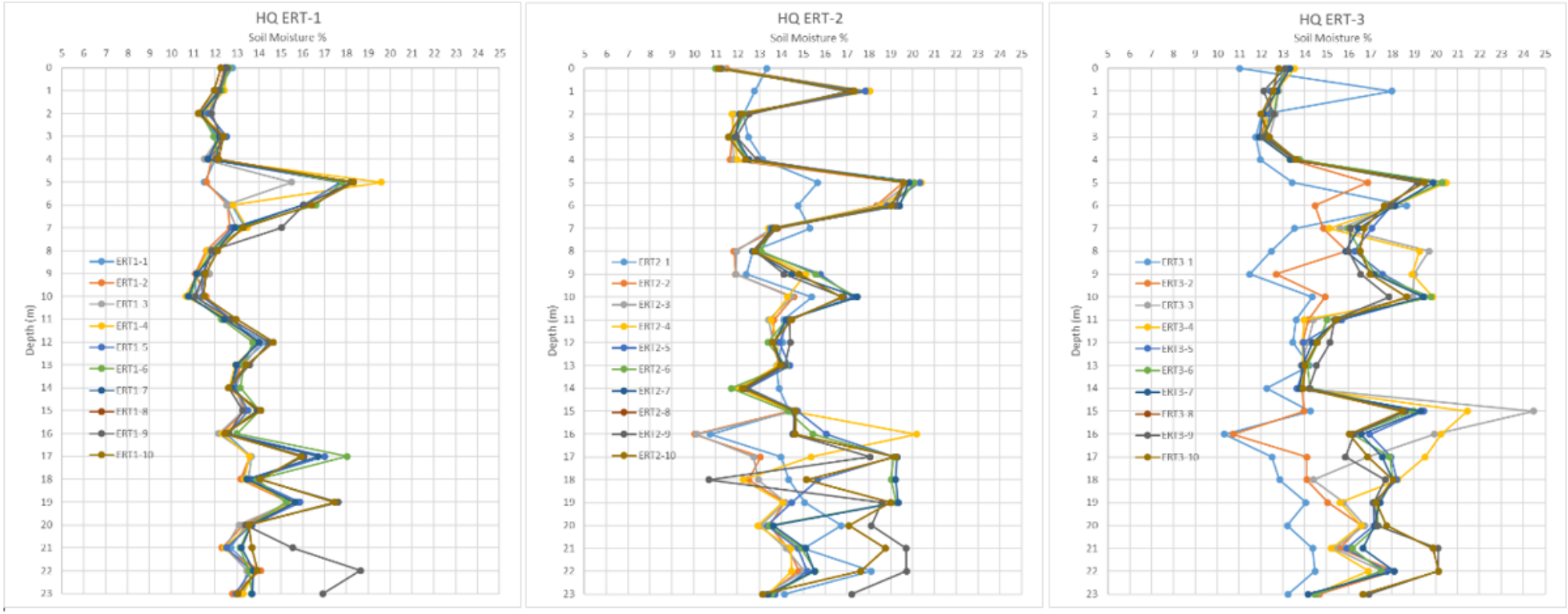
Figure 6



Note: Time-lapse neutron probe curves at the HQ site in ERT boreholes 1, 2, and 3. All wells show an increase in soil moisture at the bottom of the pretreatment and primary containment units (24ft/7m), and at the bottom of the drywell (55ft/17m). ERT-2 and ERT-3 show more water movement towards those wells versus ERT-1.

Phase I LID Study

ERT Time-lapse Results

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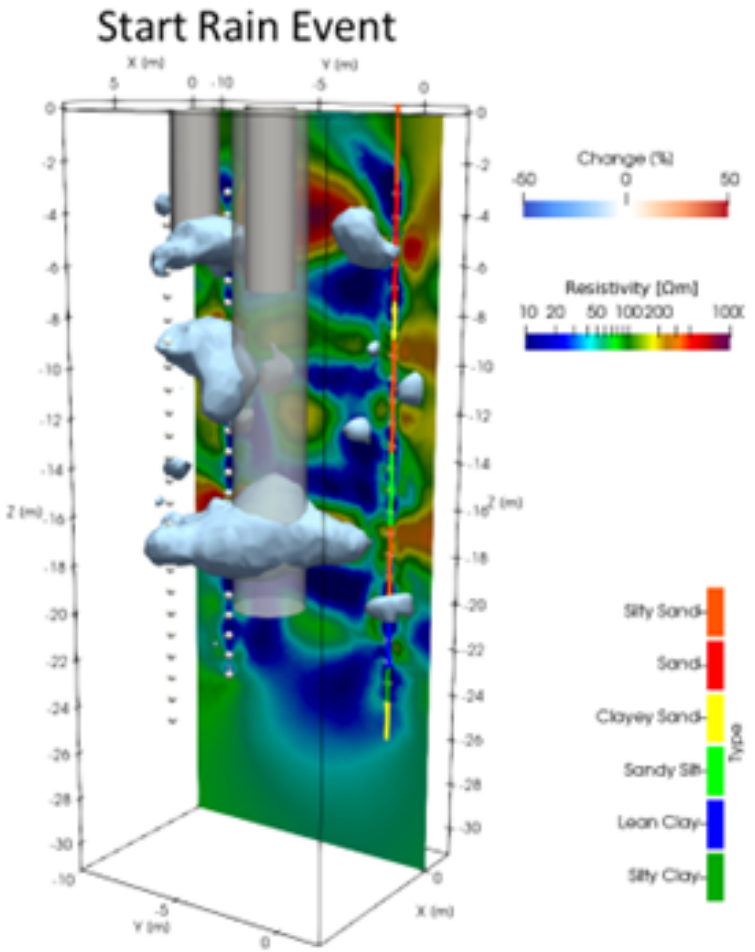
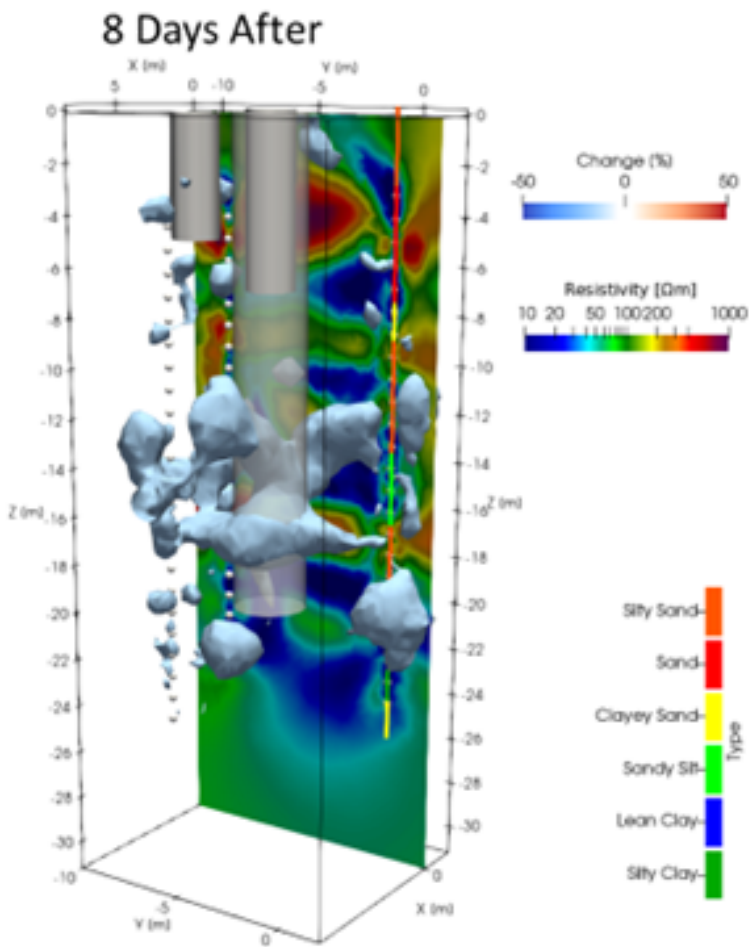
Figure 7

A)



B)



Note: ERT time-lapse data from first rain event of the season (22 December 2021 through 30 December 2021).

From left to right, images show soil conditions at the drywell **A)** prior to the start of a storm event, **B)** eight days after the event. The infiltrated water exfiltrating from the upper primary chamber (6m) can be seen at depths of 12 – 16 m after the rain event.

Phase I LID Study

Storm Event ERT Time-lapse Results

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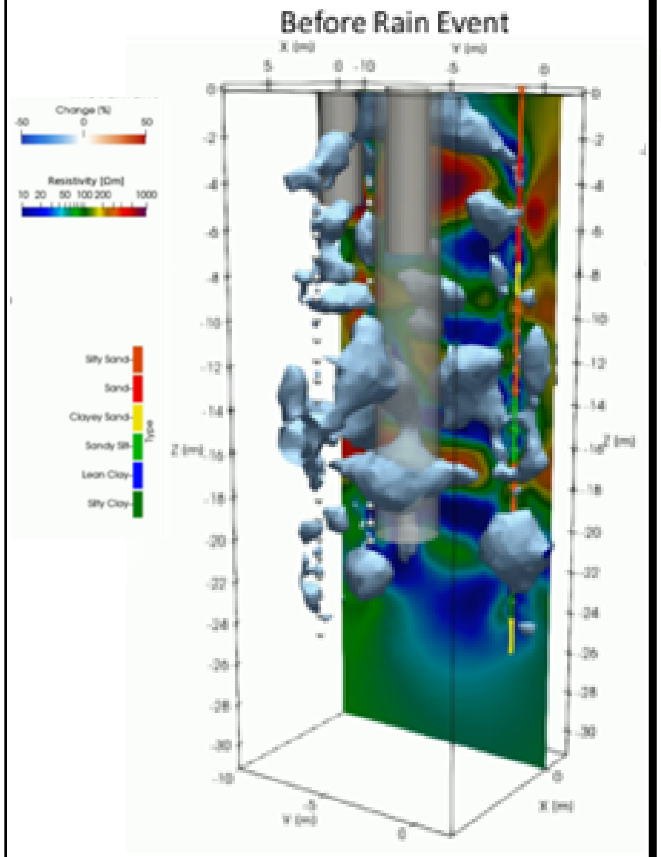
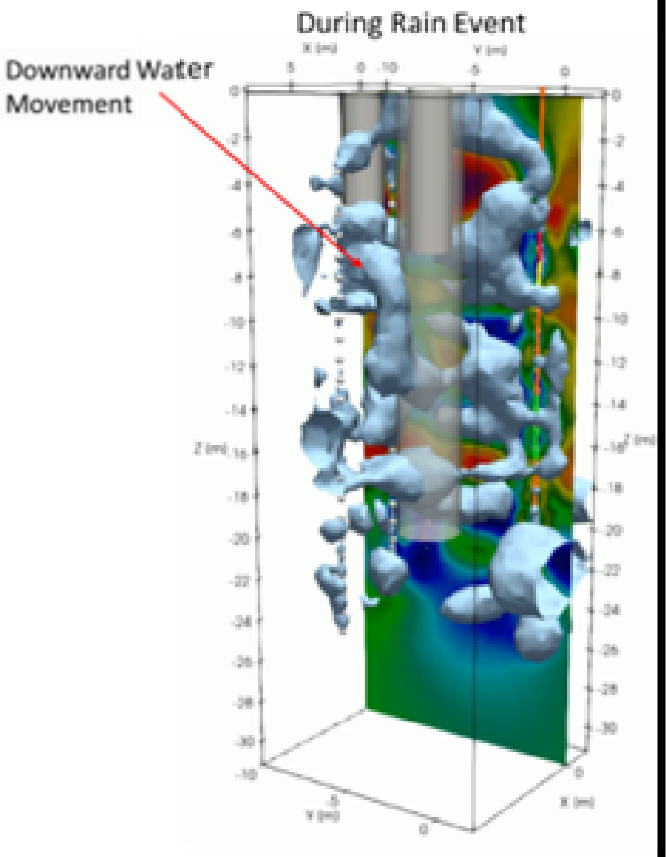
Figure 8

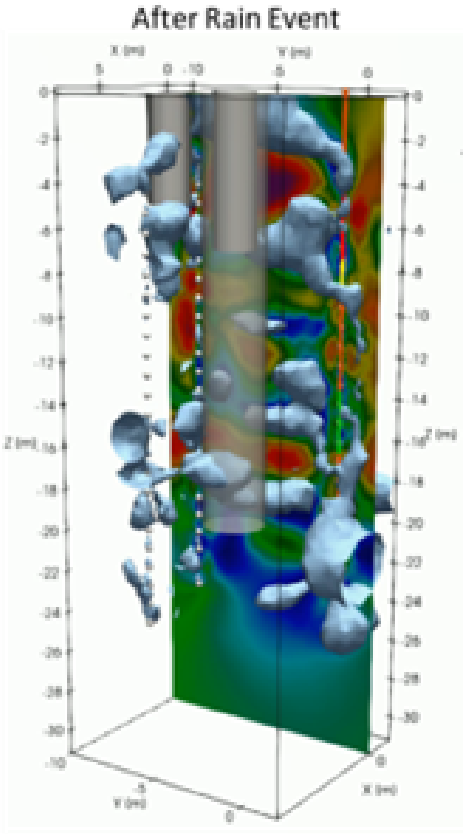
A)



B)



C)



Note: ERT time-lapse data from December 2021 through March 2022. From left to right, images show soil conditions at the drywell **A)** prior to the start of a storm event, **B)** during the precipitation event, and **C)** after the rain event.

The downward water movement along fast-paths is shown by the red arrow (Figure **9B**). Days after the rain event the majority of the water has moved away from the drywell.

Phase I LID Study

Storm Event ERT Time-lapse Results

Geosyntec consultants

CWR0869 | January 2024

Figure 9

ATTACHMENT 2

TABLES

Table 1. Soil boring results at Rosemead Blvd bioswale, collected on 25 August 2021.

Depth (ft)	Blow counts	Recovery	Sample description	Constituents	Moisture Content	Dry Density	Hydraulic Conductivity
		(%)		(gravel/sand/fines)	(%)	(pcf)	(cm/sec)
0 - 5			Silty sand: brown, dry, fine grained, NP	10/50/40			
5 - 6.5	13,13,16	100	Silty sand: light brown, dry, fine to medium grained, NP	1/79/20*	1.9	106.0	2.81X10^-4 @5.0 psi confinement
6.5 - 8	8,15,20	100		20/65/15			
8 - 9.5	8,19,21	100		0/77/23*	4.5	109.6	1.08X10^-4 @5.3 psi confinement
9.5 - 11	15,15,20	100		8/76/16*	3.4	109.0	4.23X10^-4 @6.1 psi confinement
11 - 12.5	15,20,22	80	Well-graded sand with gravel: light gray, dry, medium to coarse grained, NP	20/75/5			
12.5 - 14	20,25,32	80		25/70/5			
14 - 15.5	7,13,23	70		25/70/5			
15.5 - 17	15,24,30	70	Silty sand: gray, dry, fine to medium grained, NP	5/60/35			
17 - 18.5	13,17,21	70		10/50/40			
18.5 - 20	13,19,25	70		10/50/40			
20 - 21.5	12,12,19	95	Silty sand: gray, moist, fine grained, low plasticity	5/50/45			
21.5 - 23	Missed	95		5/55/40			
23 - 24.5	20,22,25	65	Silty sand with gravel: light gray, moist, fine to coarse grained, NP	15/50/35			
24.5 - 26	15,15,23	65		15/50/35			
26 - 27.5	20,25,25	100	Well-graded sand with silt and gravel: gray, moist, fine to coarse grained, low plasticity	15/75/10			
27.5 - 29	15,16,15	100		15/75/10			
29 - 30.5	20,22,25	100		15/75/10			
30.5 - 32	23,25,28	60		20/70/10			
32 - 33.5	20,23,25	70	Well graded sand with silt and gravel: light gray, dry, medium to coarse grained, NP	20/75/5			

* = Based on laboratory sieve analysis

Table 2. Soil boring results at LACDPW drywell.

Depth	Blow counts	Recovery	Sample description	Constituents	Moisture Content	Dry Density	Hydraulic Conductivity
		(%)		(gravel/sand/fines)	(%)	(pcf)	(cm/sec)
0 - 5			Silty sand with gravel: brown, gravel up to 2 inches				
5 - 6.5	4,4,4	100	Silty sand with gravel: brown, moist, gravel up to 2 inches, low plasticity	30/50/20			
10 - 11.5	7,9,10	100	Well graded sand with gravel: tan, moist, gravel up to 2.5 inches, NP	30/65/5			
15 - 16.5	6,14,29	100		35/60/5			
20 - 21.5	8,8,10	100		16/76/8*	4.7	120.6	2.10X10^-4 @11.9 psi confinement
25 - 26.5	4,10,19	100	Clayey sand: brown, moist, low to medium plasticity	1/51/48*	14.1	120.6	6.73X10^-7 @14.7 psi confinement
30 - 31.5	8,14,23	100	Silty sand: brown, moist, fine to medium grained, low plasticity	10/50/40			
35 - 36.5	13,14,17	100		0/76/24*	7.0	106.2	3.30X10^-4 @20.3 psi confinement
40 - 41.5	9,19,27	100		5/50/45			
45 - 46.5	7,11,21	100	Sandy silt: brown, moist, low to medium plasticity, clay pockets	5/35/60			
50 - 51.5	11,23,21	100		0/32/68*	15.0	101.2	1.04X10^-4 @28.6 psi confinement
55 - 56.5	6,14,38	100	Silty sand: brown, moist, fine to med grained, low plasticity	5/50/45			
60 - 61.5	12,19,36	100		0/83/17*	4.5	117.6	5.72X10^-5 @34.2 psi confinement
65 - 66.5	2,9,14	55	Lean clay with sand: brown, moist, medium plasticity	5/20/7 5			
70 - 71.5	6,12,25	100	Clayey sand: brown, moist, medium plasticity	6/52/42*	14.1	116.6	1.05X10^-7 @39.7 psi confinement
75 - 76.5	6,11,22	100	Silty clay: brown, moist, medium plasticity	5/25/7 0			
80 - 81.5	7,15,31	100	Clayey sand: brown, moist, low plasticity	0/73/27*	12.7	117.7	3.08X10^-5 @45.3 psi confinement

* = Based on laboratory sieve analysis

ATTACHMENT 3

FIELD MONITORING AND SAMPLING PLAN

Field Monitoring and Sampling Plan for 900 S. Fremont Ave.

Monitoring Purpose

The Fremont Ave. site will have three monitoring wells installed that will have electrical resistivity tomography (ERT) systems installed in the bore holes to monitor water dispersion between the two wells and to quantify the depth and transmissivity of applied water (stormwater).

Location

The site is located on the south side of the LACPW HQ on the south side of the parking lot adjacent to the solar panel field (Figure 1). Two monitoring wells will be placed in the in the planters and one in the aisleway of the parking lot (Figure 2).

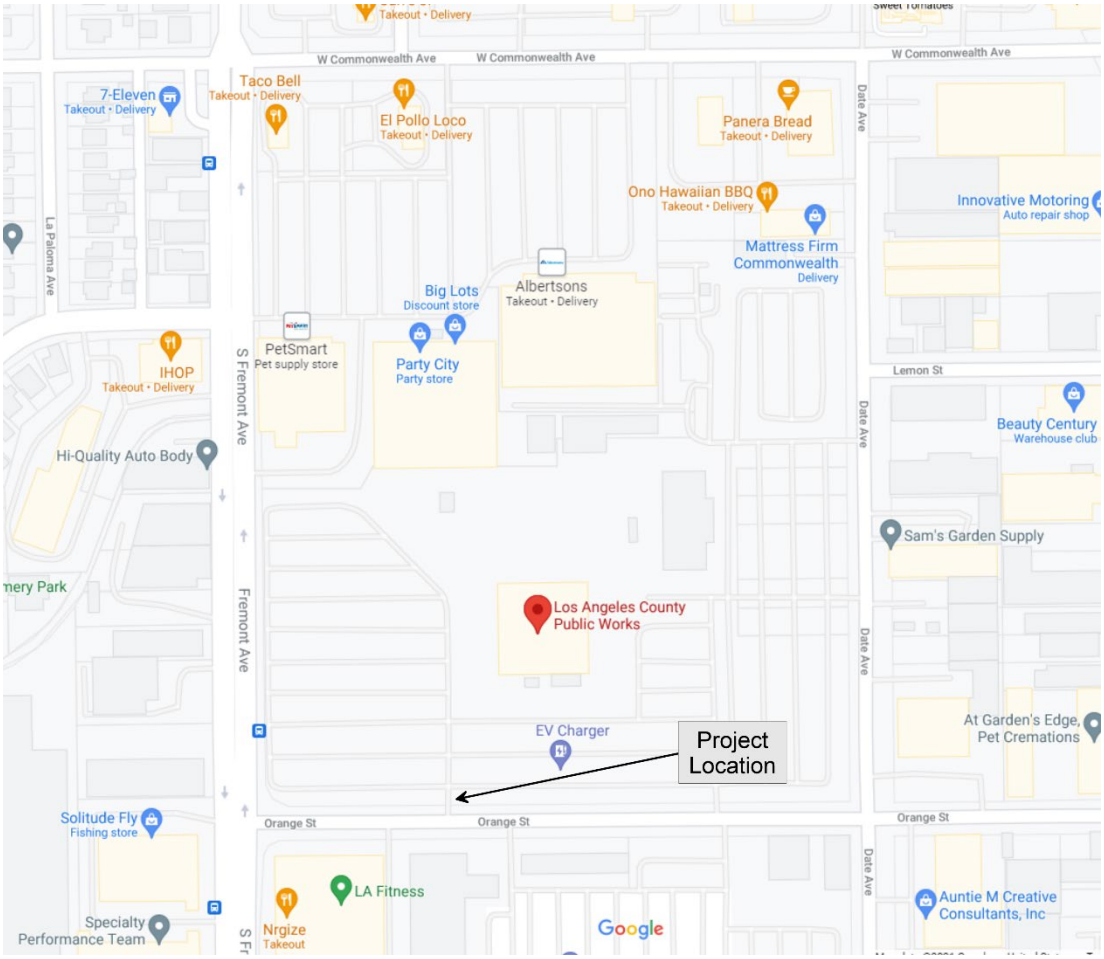


Figure 1. Map of Project Location.

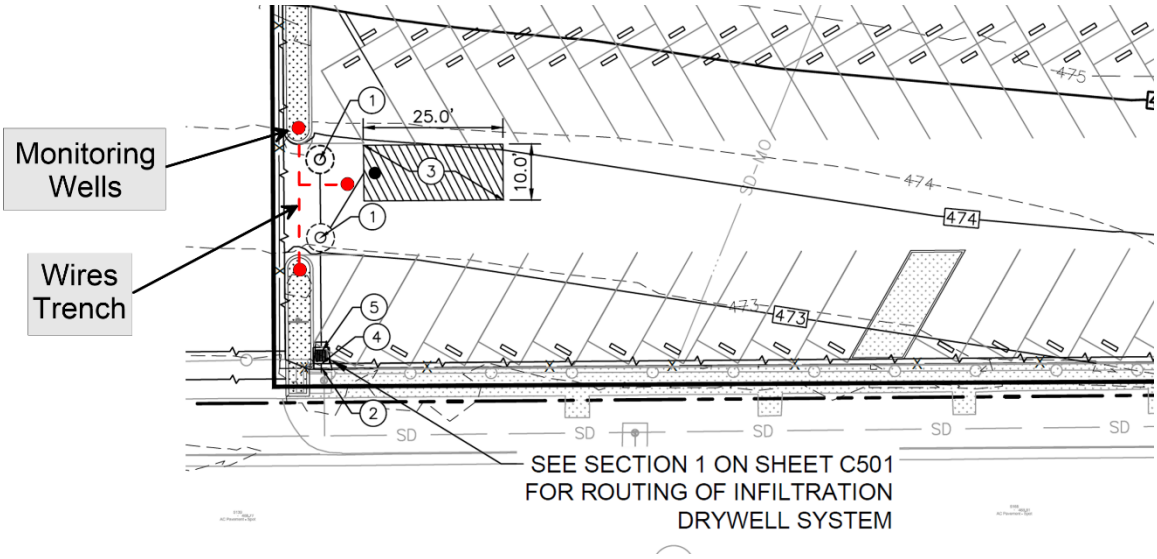


Figure 2. Approximate monitoring locations on engineering as-builts.

Monitoring Equipment

A standard 4 or 6" diameter boreholes will be made to a depth of ~80 ft below ground surface. Drill cuttings will be used to backfill the monitoring wells and unused cuttings will be collected and disposed of offsite. Two-inch PVC solid casing will be installed in the borehole with monitoring sensors attached to the PVC. The sensors (Figure 3) will be connected to the surface data logger via wires that will be ran along the outside of the casing to the top of the well. The wires will then exit the well head and enter into a saw cut trench (~3" wide by 12" deep) that will convey the wires back to a single location where the data collection system will be located. A schematic for the trench locations is shown in Figure 2.

Two experiments will take place at this location. The first will be a controlled recharge experiment where a known supply and amount of water will be delivered to the drywell system and monitoring will determine the fate of the water.

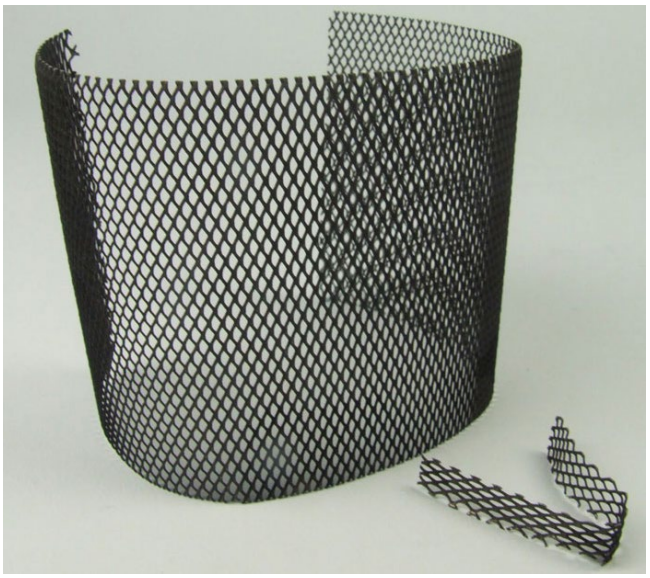


Figure 3. Wire mesh to be attached to outside of PVC.

Installation Procedures

Three groundwater wells will be installed for monitoring equipment (Figure 2).

Drilling: A truck mounted, track mounted, or limited access drilling rig (Figure 4) will be used to bore a 4 or 6" hollow stem auger to a depth of ~80 ft. Split spoon sampling will occur every 5 ft in the interval between 0 – 15 ft and then every 10 ft thereafter to log bore cuttings.



Figure 4. Examples of Potential Drill Rigs.

The ERT monitoring system mounted to 2" PVC pipe will be inserted into the bore hole. The electrical resistivity sensors will be adhered to the outside of each PVC pipe and installed in each borehole. The sensors will be connected to the surface data logger.

Drill cuttings (or sand if cuttings aren't deemed appropriate) along with bentonite clay will be used as well backfill and will be gently applied to the external anulus of the bore hole. Each well will be finished with standard monitoring well cover (Figure 5) to allow easy access and protection of the wiring system and for neutron probe deployment. Unused cuttings will be barrel stored, removed, and disposed in an offsite location. Cuttings are anticipated to be non-hazardous.



Figure 5. Example of a standard monitoring well cap and vault.

Safety Protocols

Utility plans well be reviewed and 811/Call Before You Dig services will be used to mark/document utility locations.

A Task Hazard Plan will be developed to assure safety of all field personnel.

A brief traffic control plan will be developed should traffic control be necessary.

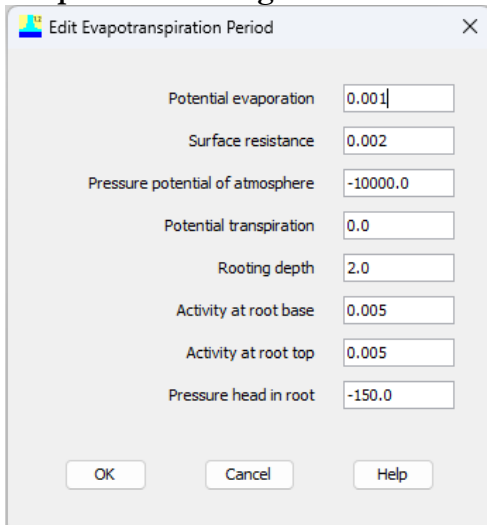
A4. Soil Data

A4.1 Rosemead

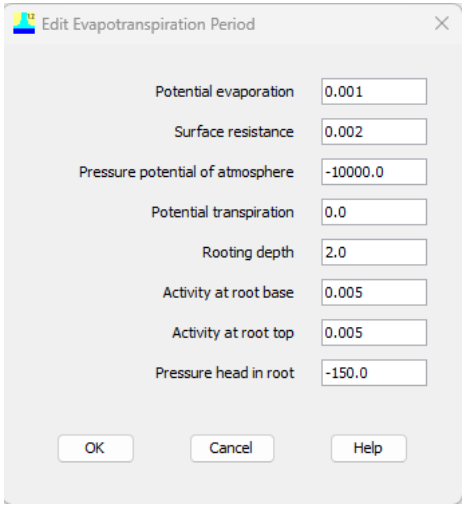
Location: Rosemead Blvd, Pasadena								
Drill date:	25-Aug-21			NP = non-plastic				
Project:	CWR0638							
Depth	**Sample type**	**Blow counts**	**Recovery**	**Sample description**	**Constituents**	**Moisture Content**	**Dry Density**	**Hydraulic Conductivity**
			(%)		**(gravel/sand/fines)**	(%)	(pcf)	(cm/sec)
0 - 5	Hand Auger			Silty sand: brown, dry, fine grained, NP	10/50/40			
5 - 6.5	Mod-Cal	13,13,16	100	Silty sand: light brown, dry, fine to medium grained, NP	1/79/20*	1.9	106.0	2.81X10^-4 @5.0 psi confinement
6.5 - 8	SPT	8,15,20	100		20/65/15			
8 - 9.5	Mod-Cal	8,19,21	100		0/77/23*	4.5	109.6	1.08X10^-4 @5.3 psi confinement
9.5 - 11	Mod-Cal	15,15,20	100		8/76/16*	3.4	109.0	4.23X10^-4 @6.1 psi confinement
11 - 12.5	SPT	15,20,22	80	Well-graded sand with gravel: light gray, dry, medium to coarse grained, NP	20/75/5			
12.5 - 14	SPT	20,25,32	80		25/70/5			
14 - 15.5	SPT	7,13,23	70		25/70/5			
15.5 - 17	SPT	15,24,30	70	Silty sand: gray, dry, fine to medium grained, NP	5/60/35			
17 - 18.5	SPT	13,17,21	70		10/50/40			
18.5 - 20	SPT	13,19,25	70		10/50/40			
20 - 21.5	SPT	12,12,19	95	Silty sand: gray, moist, fine grained, low plasticity	5/50/45			
21.5 - 23	SPT	Missed	95		5/55/40			
23 - 24.5	SPT	20,22,25	65	Silty sand with gravel: light gray, moist, fine to coarse grained, NP	15/50/35			
24.5 - 26	SPT	15,15,23	65		15/50/35			
26 - 27.5	SPT	20,25,25	100		15/75/10			

27.5 - 29	SPT	15,16,15	100	Well-graded sand with silt and gravel: gray, moist, fine to coarse grained, low plasticity	15/75/10			
29 - 30.5	SPT	20,22,25	100		15/75/10			
30.5 - 32	SPT	23,25,28	60		20/70/10			
32 - 33.5	SPT	20,23,25	70	Well graded sand with silt and gravel: light gray, dry, medium to coarse grained, NP	20/75/5			
					* = Based on laboratory sieve analysis			

Evaporation Settings



Transpiration Settings



A4.2 Headquarters

Location:	LACPW Headquarters, Alhambra						
Boring:	ERT-1						
Drill date:				NP = non-plastic			
Project:	CWR0638						
Depth	**Sample type**	**Blow counts**	**Recovery**	**Sample description**	**Constituents**	**Moisture Content**	**Dry Density**	**Hydraulic Conductivity**
			(%)		(gravel/sand/fines)	(%)	(pcf)	(cm/sec)
0 - 5	Hand Auger			Silty sand with gravel: brown, gravel up to 2 inches				
5 - 6.5	Mod-Cal	4,4,4	100		30/50/20			
10 - 11.5	Mod-Cal	7,9,10	100		30/65/5			
15 - 16.5	Mod-Cal	6,14,29	100		35/60/5			
20 - 21.5	Mod-Cal	8,8,10	100		16/76/8*	4.7	120.6	2.10X10^-4 @11.9 psi confinement
25 - 26.5	Mod-Cal	4,10,19	100		1/51/48*	14.1	120.6	6.73X10^-7 @14.7 psi confinement
30 - 31.5	Mod-Cal	8,14,23	100		10/50/40			
35 - 36.5	Mod-Cal	13,14,17	100		0/76/24*	7	106.2	3.30X10^-4 @20.3 psi confinement
40 - 41.5	Mod-Cal	9,19,27	100		5/50/45			
45 - 46.5	Mod-Cal	7,11,21	100		5/35/60			
50 - 51.5	Mod-Cal	11,23,21	100		0/32/68*	15	101.2	1.04X10^-4 @28.6 psi confinement
55 - 56.5	Mod-Cal	6,14,38	100		5/50/45			
60 - 61.5	Mod-Cal	12,19,36	100		0/83/17*	4.5	117.6	5.72X10^-5 @34.2 psi confinement
65 - 66.5	Mod-Cal	2,9,14	55		5/20/7 5			
70 - 71.5	Mod-Cal	6,12,25	100	Clayey sand: brown, moist,	6/52/42*	14.1	116.6	1.05X10^-7 @39.7 psi confinement

75 - 76.5	Mod-Cal	6,11,22	100	medium plasticity	5/25/7 0			
80 - 81.5	Mod-Cal	7,15,31	100		0/73/27*	12.7	117.7	3.08X10^-5 @45.3 psi confinement
								* = Based on laboratory sieve analysis

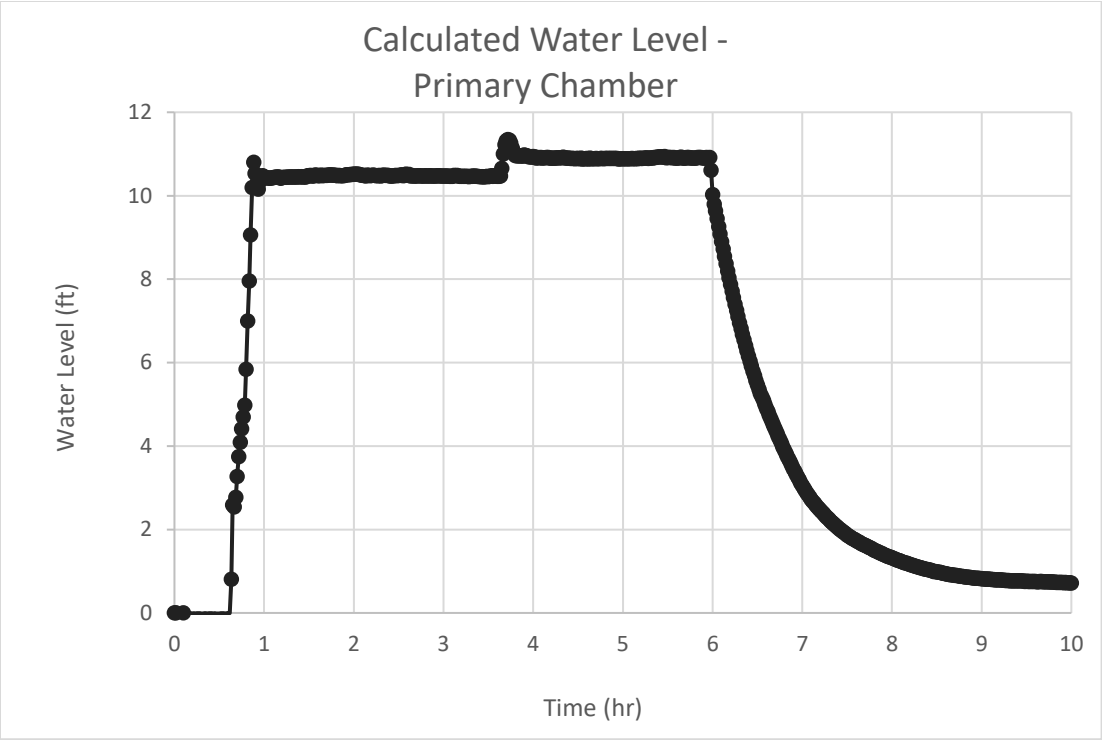
A4.3 Van Nuys

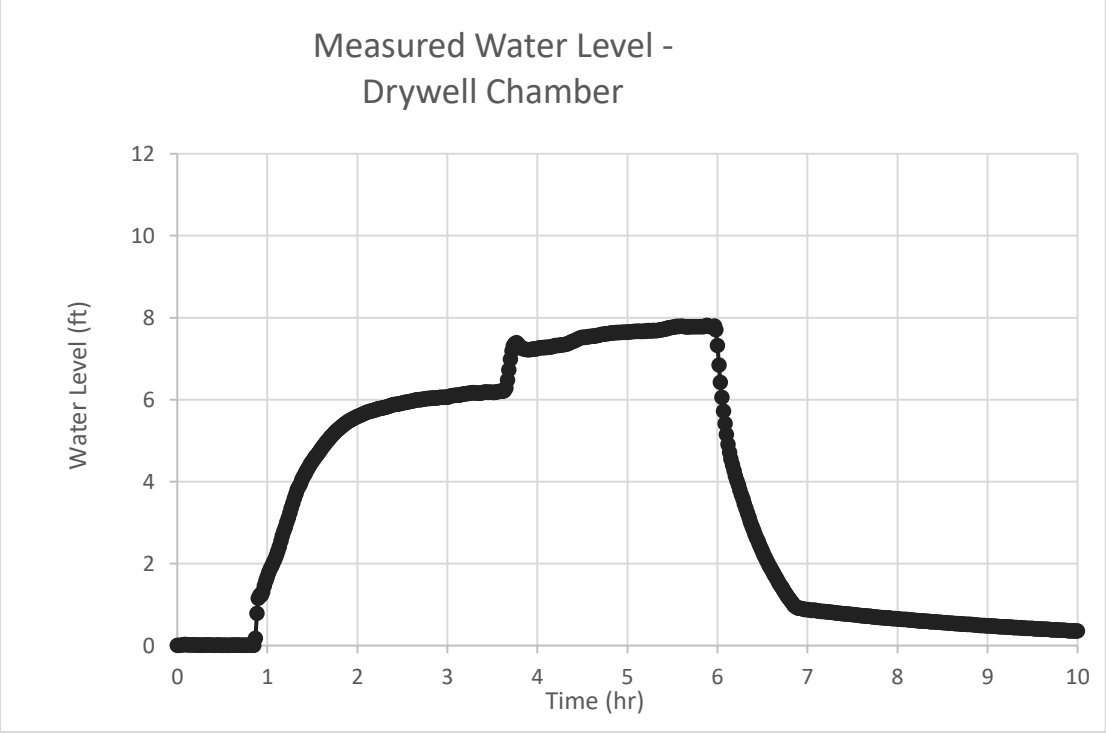
Location:	El Dorado Ave. and Mercer St., Los Angeles (Van Nuys Site)						
Boring:	ERT-5						
Drill date:	7-Oct-24	NP = non-plastic					
Project:	CWR0869						
Depth	**Sample type**	**Sample description**	**Percent of Soil Constituents**				**Moisture Content[4]**
			Gravel	**Sand**	**Silt**	**Clay**	(%)
0 - 5	Hand Auger	SILTY SAND, yellowish brown, moist, fine to medium, few gravel approx. 2" diameter subangular.					
5 - 6.5	Split-spoon	SAA; fine to coarse, approx. 1" diameter gravel subangular.					
10 - 11.5	Split-spoon	WELL GRADED SAND WITH SILT AND GRAVEL (SW-SM), olive to yellowish brown, fine to coarse gravel, rounded to subangular.	25%	63%	10%	2%	0.77%
15 - 16.5	Split-spoon						
20 - 21.5	Split-spoon	SILTY SAND WITH GRAVEL (SM), olive to yellowish brown	19%	68%	9%	4%	0.64%
25 - 26.5	Split-spoon						
30 - 31.5	Split-spoon	POORLY GRADED SAND WITH SILT AND GRAVEL (SP-SM), olive to yellowish brown, fine to coarse gravel, subangular	37%	55%	6%	2%	0.55%

35 - 36.5	Split-spoon	SILTY SAND (SM), yellowish brown and gray, fine to coarse, few gravel of 1" diameter					
40 - 41.5	Split-spoon	SILTY SAND WITH GRAVEL (SM), yellowish brown to gray, fine to coarse					
45 - 46.5	Split-spoon	SAA.					
50 - 51.5	Split-spoon	SILTY SAND WITH GRAVEL (SM), reddish brown to olive, fine to medium gravel	33%	53%	14%	2%	1.76%
55 - 56.5	Split-spoon	SILTY SAND (SM), tan, fine to coarse, trace gravel about 1" diameter					
60 - 61.5	Split-spoon	WELL GRADED SAND WITH SILT AND GRAVEL (SW-SM), olive to ta, medium to coarse gravel about 1" diameter.	23%	69%	6%	2%	0.48%
65 - 66.5	Split-spoon	SAA, reddish brown					
70 - 71.5	Split-spoon	SAA, yellowish brown					
75 - 77	Split-spoon						
NOTES:							

1. Surface Conditions: 9" Asphalt; Approx. 6" of base material.
2. SPT was not performed, therefore blow counts were not recorded.
3. Values provided based on laboratory tests performed by Geosyntec, Particle-Size Analysis of Soils (Sieve + Hydrometer)
4. Moisture Content performed by Lawrence Berkeley Laboratory.
5. SAA: Same As Above

A5. Synthetic Storm Event Water Levels – Headquarters Drywell





A6. Volumetric Water Content Data (θ) from Neutron Probes

A6.1 Rosemead – Synthetic Storm Event 1

Data

Table 18. Rosemead Bioswale – VWC (θ) observations for synthetic storm event 1 (neutron probes 1 & 2)

	Neutron Probe 1				Neutron Probe 2			
	Time Stamp (hr)				Time Stamp (hr)			
	0.0	2.3	5.6	7.4	0.0	2.3	5.6	7.4
Depth (ft)	Volumetric Water Content (θ)				Volumetric Water Content (θ)			
1.6	2.1	19.6	20.0	19.3	16.5	20.6	20.6	20.6
3.3	9.9	10.2	20.1	20.1	9.4	13.0	14.4	14.7
4.9	7.9	8.3	18.4	18.7	8.2	7.9	18.5	18.7
6.6	8.9	7.8	8.7	15.9	8.5	8.8	13.8	17.4
8.2	9.5	8.6	8.4	8.3	8.3	9.0	9.4	9.5
9.8	8.6	10.3	10.4	10.2	10.2	8.5	8.6	8.8
11.5	7.7	10.5	10.2	10.2	10.2	7.8	7.6	8.0
13.1	10.8	7.8	7.7	7.8	7.9	10.9	11.1	10.8
14.8	8.2	7.8	7.9	7.9	7.9	8.2	8.3	8.0
16.4	10.2	8.6	8.5	8.7	8.7	10.3	10.5	10.8
18.0	8.6	8.5	8.3	8.3	8.0	8.6	8.4	8.4
19.7	8.0	10.8	10.9	10.5	10.6	8.1	7.9	8.0
21.3	9.5	8.9	8.7	8.9	8.7	9.7	9.4	9.2
23.0	9.0	8.6	8.7	8.4	8.4	9.3	9.2	9.0
24.6	10.7	8.7	8.3	8.5	8.7	10.9	11.0	10.8
26.2	8.6	7.5	7.4	7.5	7.5	8.3	8.6	8.6
27.9	9.2	7.8	7.4	7.9	7.6	8.9	9.0	9.2
29.5	7.9	6.3	6.1	6.2	6.3	7.8	8.1	8.0
31.2	5.3	5.7	5.7	5.7	5.8	5.9	5.6	5.3
32.8	6.3	6.5	6.4	6.6	6.5	6.4	6.3	6.3

Data Analysis – Probe 1

Table 19. Rosemead Bioswale – Increases in VWC (θ) ≥ 1.5% marked in yellow and orange for synthetic storm event 1 (neutron probe 1)

Neutron Probe 1							
	Time Stamp (hr)				DELTA θ		
	0.0	2.3	5.6	7.4			
Depth (ft)	Volumetric Water Content (θ)				2.3 - 0.0	5.6 - 0.0	7.4 - 0.0
1.6	2.1	19.6	20.0	19.3	17.5	17.8	17.2
3.3	9.9	10.2	20.1	20.1	0.3	10.2	10.2
4.9	7.9	8.3	18.4	18.7	0.4	10.5	10.8
6.6	8.9	7.8	8.7	15.9	-1.1	-0.2	7.0
8.2	9.5	8.6	8.4	8.3	-0.9	-1.1	-1.2
9.8	8.6	10.3	10.4	10.2	1.7	1.8	1.7
11.5	7.7	10.5	10.2	10.2	2.8	2.5	2.5
13.1	10.8	7.8	7.7	7.8	-3.1	-3.2	-3.1
14.8	8.2	7.8	7.9	7.9	-0.4	-0.2	-0.3
16.4	10.2	8.6	8.5	8.7	-1.6	-1.7	-1.5
18.0	8.6	8.5	8.3	8.3	-0.2	-0.4	-0.4
19.7	8.0	10.8	10.9	10.5	2.9	3.0	2.6
21.3	9.5	8.9	8.7	8.9	-0.6	-0.8	-0.6
23.0	9.0	8.6	8.7	8.4	-0.4	-0.4	-0.6
24.6	10.7	8.7	8.3	8.5	-2.0	-2.4	-2.2
26.2	8.6	7.5	7.4	7.5	-1.1	-1.1	-1.1
27.9	9.2	7.8	7.4	7.9	-1.4	-1.8	-1.3
29.5	7.9	6.3	6.1	6.2	-1.6	-1.8	-1.7
31.2	5.3	5.7	5.7	5.7	0.4	0.4	0.4
32.8	6.3	6.5	6.4	6.6	0.2	0.1	0.3

Data Analysis – Probe 2

Table 20. Rosemead Bioswale – Increases in VWC (θ) ≥ 1.5% marked in yellow and orange for synthetic storm event 1 (neutron probe 2)

Neutron Probe 2							
	Time Stamp (hr)				DELTA θ		
	0.0	2.3	5.6	7.4			
Depth (ft)	Volumetric Water Content (θ)				2.3 - 0.0	5.6 - 0.0	7.4 - 0.0
1.6	16.5	20.6	20.6	20.6	4.1	4.1	4.1
3.3	9.4	13.0	14.4	14.7	3.6	5.0	5.2
4.9	8.2	7.9	18.5	18.7	-0.2	10.4	10.5
6.6	8.5	8.8	13.8	17.4	0.3	5.3	9.0
8.2	8.3	9.0	9.4	9.5	0.7	1.1	1.2
9.8	10.2	8.5	8.6	8.8	-1.8	-1.6	-1.4
11.5	10.2	7.8	7.6	8.0	-2.4	-2.6	-2.2
13.1	7.9	10.9	11.1	10.8	3.0	3.3	2.9
14.8	7.9	8.2	8.3	8.0	0.2	0.3	0.1
16.4	8.7	10.3	10.5	10.8	1.7	1.8	2.1
18.0	8.0	8.6	8.4	8.4	0.6	0.4	0.4
19.7	10.6	8.1	7.9	8.0	-2.5	-2.7	-2.6
21.3	8.7	9.7	9.4	9.2	1.0	0.7	0.5
23.0	8.4	9.3	9.2	9.0	0.9	0.8	0.6
24.6	8.7	10.9	11.0	10.8	2.2	2.3	2.1
26.2	7.5	8.3	8.6	8.6	0.8	1.2	1.1
27.9	7.6	8.9	9.0	9.2	1.3	1.4	1.5
29.5	6.3	7.8	8.1	8.0	1.6	1.8	1.8
31.2	5.8	5.9	5.6	5.3	0.1	-0.2	-0.5
32.8	6.5	6.4	6.3	6.3	-0.2	-0.2	-0.2

A6.2 Rosemead – Synthetic Storm Event 2

Data

Table 21. Rosemead Bioswale – VWC (θ) observations for synthetic storm event 2 (neutron probes 1 & 2)

	Neutron Probe 1			Neutron Probe 2		
	Time Stamp (hr)			Time Stamp (hr)		
	0.0	5.6	20.8	0.0	5.6	19.6
Depth (ft)	Volumetric Water Content (θ)			Volumetric Water Content (θ)		
1.6	20.6	23.9	21.1	2.2	5.9	5.3
3.3	13.9	17.5	16.2	15.1	23.4	20.4
4.9	12.2	16.3	16.3	5.3	26.8	8.3
6.6	12.0	12.7	14.5	12.5	16.4	16.6
8.2	12.2	12.3	12.7	11.9	12.0	12.6
9.8	13.1	13.6	13.2	13.2	13.4	13.5
11.5	12.3	12.3	12.1	13.7	13.8	14.1
13.1	11.6	11.7	11.7	13.8	14.2	14.3
14.8	10.7	10.9	11.0	14.6	14.4	14.4
16.4	13.0	12.9	12.8	14.2	13.7	14.1
18.0	12.9	13.2	13.2	15.2	14.4	14.9
19.7	13.4	8.0	12.9	13.9	14.0	14.1
21.3	15.1	15.1	15.2	15.1	14.9	14.7
23.0	14.9	14.7	14.8	14.0	14.5	14.1
24.6	13.9	13.7	13.5	14.4	14.6	14.6
26.2	12.1	12.4	12.7	13.2	13.0	13.1
27.9	11.3	11.2	11.3	13.5	13.5	13.9
29.5	—	—	—	12.1	12.4	12.3

Data Analysis – Probe 1

Table 22. Rosemead Bioswale – Increases in VWC (θ) ≥ 1.5% marked in yellow and orange for synthetic storm event 2 (neutron probe 1)

Neutron Probe 1					
	Time Stamp (hr)			DELTA θ	
	0.0	5.6	20.8		
Depth (ft)	Volumetric Water Content (θ)			5.6 - 0.0	20.8 - 0.0
1.6	20.6	23.9	21.1	3.3	0.5
3.3	13.9	17.5	16.2	3.7	2.3
4.9	12.2	16.3	16.3	4.1	4.0
6.6	12.0	12.7	14.5	0.7	2.5
8.2	12.2	12.3	12.7	0.1	0.5
9.8	13.1	13.6	13.2	0.5	0.1
11.5	12.3	12.3	12.1	0.0	-0.1
13.1	11.6	11.7	11.7	0.1	0.0
14.8	10.7	10.9	11.0	0.2	0.3
16.4	13.0	12.9	12.8	-0.1	-0.2
18.0	12.9	13.2	13.2	0.3	0.3
19.7	13.4	8.0	12.9	-5.4	-0.5
21.3	15.1	15.1	15.2	0.1	0.2
23.0	14.9	14.7	14.8	-0.2	0.0
24.6	13.9	13.7	13.5	-0.2	-0.4
26.2	12.1	12.4	12.7	0.3	0.5
27.9	11.3	11.2	11.3	-0.1	0.0
29.5	—	—	—	NA	NA

Data Analysis – Probe 2

Table 23. Rosemead Bioswale – Increases in VWC (θ) ≥ 1.5% marked in yellow and orange for synthetic storm event 2 (neutron probe 2)

Neutron Probe 2					
	Time Stamp (hr)			DELTA θ	
	0.0	5.6	19.6		
Depth (ft)	Volumetric Water Content (θ)			5.6 - 0.0	19.6 - 0.0
1.6	2.2	5.9	5.3	3.7	3.2
3.3	15.1	23.4	20.4	8.3	5.3
4.9	5.3	26.8	8.3	21.6	3.1
6.6	12.5	16.4	16.6	3.9	4.1
8.2	11.9	12.0	12.6	0.1	0.6
9.8	13.2	13.4	13.5	0.2	0.4
11.5	13.7	13.8	14.1	0.1	0.4
13.1	13.8	14.2	14.3	0.4	0.5
14.8	14.6	14.4	14.4	-0.2	-0.3
16.4	14.2	13.7	14.1	-0.5	0.0
18.0	15.2	14.4	14.9	-0.8	-0.2
19.7	13.9	14.0	14.1	0.1	0.2
21.3	15.1	14.9	14.7	-0.2	-0.4
23.0	14.0	14.5	14.1	0.5	0.2
24.6	14.4	14.6	14.6	0.2	0.2
26.2	13.2	13.0	13.1	-0.1	0.0
27.9	13.5	13.5	13.9	0.0	0.4
29.5	12.1	12.4	12.3	0.3	0.2

A6.3 Headquarters – Synthetic Storm Event

Data

Table 24. Headquarters Drywell – VWC (θ) observations for the synthetic storm event (neutron probes 1, 2, & 3)

	Neutron Probe 1									Neutron Probe 2									Neutron Probe 3								
	Time (hr)									Time (hr)									Time (hr)								
	0.0	2.5	4.7	6.6	20.6	25.8	29.7	43.8	77.4	0.0	2.5	4.7	6.6	20.6	25.8	29.7	43.8	77.4	0.0	2.5	4.7	6.6	20.6	25.8	29.7	43.8	77.4
Depth (ft)	Volumetric Water Content (%)									Volumetric Water Content (%)									Volumetric Water Content (%)								
3.3	12.8	12.4	12.5	12.5	12.4	12.7	12.5	12.3	12.6	13.3	11.5	11.4	11.2	11.1	11.0	11.2	11.1	11.2	11.0	13.2	13.3	13.5	13.2	13.1	13.3	12.8	13.1
6.6	12.1	12.2	12.2	12.4	12.3	12.3	12.2	11.9	12.1	12.8	17.9	17.9	18.1	17.8	17.3	17.3	17.3	17.1	18.0	12.7	12.8	12.7	12.4	12.8	12.7	12.6	12.1
9.8	11.3	11.2	11.3	11.4	11.7	11.4	11.3	11.2	11.8	12.3	12.3	11.8	11.7	12.2	12.3	12.1	12.2	12.5	12.0	12.3	12.7	12.3	12.4	12.6	12.1	12.0	12.6
13.1	12.1	12.5	12.2	12.3	12.5	11.9	12.2	12.4	12.3	12.5	11.7	11.8	11.9	11.9	11.9	11.9	11.6	11.9	11.8	12.0	12.4	12.2	12.2	12.0	11.9	12.4	12.1
16.4	12.0	11.8	11.5	11.8	11.7	12.1	11.7	12.1	12.0	13.2	11.6	11.8	12.0	12.4	12.4	12.5	12.4	12.9	12.0	13.4	13.7	13.3	13.7	13.8	13.4	13.6	13.6
19.7	11.5	11.6	15.5	19.6	17.7	17.8	18.3	18.3	18.2	15.7	19.6	19.9	20.4	20.3	20.1	19.8	19.6	19.6	13.4	16.9	20.4	20.5	20.3	20.3	19.9	19.5	19.2
23.0	12.8	12.6	12.5	12.8	16.0	16.6	16.0	16.4	16.1	14.8	18.3	18.5	18.5	18.9	19.3	19.4	19.0	19.2	18.7	14.5	18.1	18.1	18.0	18.0	18.1	17.6	17.9
26.2	13.4	12.7	13.0	13.5	12.8	13.0	12.9	13.3	15.0	15.3	13.8	13.6	13.4	13.5	13.6	13.6	13.7	13.8	13.5	14.9	15.6	15.1	17.1	16.0	16.5	16.7	16.1
29.5	11.7	11.6	11.7	11.6	11.8	11.9	12.1	12.1	11.8	12.7	11.8	12.0	13.0	12.9	13.1	12.7	12.8	12.8	12.5	15.9	19.7	19.3	16.3	16.5	15.9	16.5	16.0
32.8	11.1	11.1	11.7	11.2	11.4	11.2	11.2	11.6	11.5	12.4	11.9	11.9	15.1	15.8	15.6	14.5	14.8	14.1	11.5	12.7	19.0	18.9	17.6	17.2	17.2	17.0	16.6
36.1	11.1	11.6	11.1	10.7	11.4	10.9	10.8	11.5	11.1	15.4	14.6	14.5	14.3	17.3	17.5	17.5	16.8	16.8	14.4	14.9	18.9	19.9	19.5	19.8	19.4	18.7	17.9
39.4	12.4	12.6	12.4	12.6	12.7	12.3	12.4	13.0	12.7	14.1	13.7	13.4	13.5	14.3	14.2	14.2	14.5	14.4	13.6	14.2	14.4	14.0	15.7	15.0	15.5	15.5	15.4
42.7	14.3	13.9	14.1	14.0	13.9	13.7	14.0	14.7	14.5	14.1	13.6	13.6	13.8	13.9	13.4	13.6	13.6	14.4	13.5	13.9	14.1	13.9	13.9	14.6	14.4	14.6	15.2
45.9	13.1	13.1	13.3	12.9	13.0	13.3	13.0	13.4	13.6	13.8	14.0	14.1	13.8	14.4	14.2	14.1	14.0	14.2	14.2	14.1	13.8	13.9	14.0	14.1	13.9	14.0	14.5
49.2	12.8	12.9	12.9	12.7	12.9	13.2	12.7	12.6	12.6	13.9	12.4	12.3	12.1	12.5	11.7	12.3	12.2	12.4	12.3	13.9	13.9	13.8	13.7	14.3	13.8	13.9	14.2
52.5	13.9	13.4	13.3	13.9	13.5	14.0	13.9	14.1	13.3	14.4	14.3	14.6	14.5	14.8	14.3	14.6	14.7	14.6	14.3	14.0	24.5	21.4	19.4	19.0	19.3	18.5	18.6
55.8	12.5	12.3	12.2	12.3	12.6	13.0	12.5	12.4	12.6	10.7	10.0	10.1	20.2	16.1	15.4	14.6	14.6	14.5	10.3	10.7	19.9	20.2	17.0	16.2	16.6	16.0	16.3
59.1	13.6	13.6	13.7	13.6	17.0	18.0	16.7	15.9	16.1	14.0	13.0	12.7	15.4	19.2	19.1	19.3	19.2	18.1	12.5	14.1	16.9	19.5	17.9	17.9	17.6	16.9	15.9
62.3	13.2	13.2	13.5	13.3	13.6	13.9	13.5	14.1	14.0	14.3	12.5	13.0	12.3	15.7	19.0	19.2	15.2	10.7	12.9	14.1	14.4	18.3	18.2	18.0	18.0	18.0	17.7
65.6	15.8	15.4	15.4	15.5	15.9	15.2	15.7	17.5	17.6	15.1	14.2	14.2	14.1	14.5	19.3	19.4	19.0	18.6	14.1	15.1	15.8	15.6	17.1	17.3	17.4	17.3	17.2
68.9	13.4	13.3	13.1	13.6	13.7	13.6	13.6	13.5	13.4	16.8	13.5	13.1	12.9	13.4	13.5	13.6	17.1	18.1	13.2	16.6	16.7	16.6	17.2	17.4	17.2	17.7	17.3
72.2	12.7	12.3	12.5	12.4	12.5	13.1	13.2	13.7	15.5	15.0	14.3	14.2	14.4	14.8	14.9	15.1	18.8	19.7	14.4	15.6	15.3	15.2	15.9	16.2	16.7	19.9	20.1
75.5	13.9	14.1	13.4	13.8	13.7	13.5	13.8	13.9	18.6	18.1	14.8	15.0	14.5	15.2	15.5	15.5	17.6	19.7	14.5	18.1	17.6	16.9	17.8	17.5	18.1	20.1	20.1
78.7	13.2	12.8	13.2	13.3	12.9	13.7	13.7	13.0	16.9	14.1	13.4	13.3	13.4	13.7	13.6	13.4	13.1	17.2	13.2	14.7	14.6	14.5	14.5	14.5	14.1	16.7	16.9

Table 25. Headquarters Drywell – Increases in VWC (θ) ≥ 1.5% marked in yellow and orange for the synthetic storm event (neutron probe 1)

Neutron Probe 1																	
	Time Stamp (hr)									DELTA θ							
	0.0	2.5	4.7	6.6	20.6	25.8	29.7	43.8	77.4								
Depth (ft)	Volumetric Water Content (%)									2.5 - 0.0	4.7 - 0.0	6.6 - 0.0	20.6 - 0.0	25.8 - 0.0	29.7 - 0.0	43.8 - 0.0	77.4 - 0.0
3.3	12.8	12.4	12.5	12.5	12.4	12.7	12.5	12.3	12.6	-0.4	-0.3	-0.3	-0.3	-0.1	-0.3	-0.5	-0.2
6.6	12.1	12.2	12.2	12.4	12.3	12.3	12.2	11.9	12.1	0.1	0.1	0.3	0.2	0.2	0.1	-0.2	0.0
9.8	11.3	11.2	11.3	11.4	11.7	11.4	11.3	11.2	11.8	-0.1	0.0	0.1	0.4	0.1	0.0	-0.1	0.5
13.1	12.1	12.5	12.2	12.3	12.5	11.9	12.2	12.4	12.3	0.4	0.1	0.2	0.4	-0.1	0.1	0.3	0.2
16.4	12.0	11.8	11.5	11.8	11.7	12.1	11.7	12.1	12.0	-0.2	-0.5	-0.2	-0.3	0.1	-0.3	0.2	0.1
19.7	11.5	11.6	15.5	19.6	17.7	17.8	18.3	18.3	18.2	0.1	4.0	8.1	6.2	6.3	6.8	6.8	6.7
23.0	12.8	12.6	12.5	12.8	16.0	16.6	16.0	16.4	16.1	-0.2	-0.2	0.1	3.3	3.8	3.3	3.7	3.3
26.2	13.4	12.7	13.0	13.5	12.8	13.0	12.9	13.3	15.0	-0.7	-0.4	0.1	-0.6	-0.4	-0.5	-0.1	1.7
29.5	11.7	11.6	11.7	11.6	11.8	11.9	12.1	12.1	11.8	-0.1	0.0	-0.1	0.1	0.2	0.4	0.4	0.2
32.8	11.1	11.1	11.7	11.2	11.4	11.2	11.2	11.6	11.5	0.0	0.6	0.1	0.3	0.1	0.0	0.4	0.4
36.1	11.1	11.6	11.1	10.7	11.4	10.9	10.8	11.5	11.1	0.5	0.0	-0.4	0.3	-0.2	-0.3	0.4	0.0
39.4	12.4	12.6	12.4	12.6	12.7	12.3	12.4	13.0	12.7	0.2	0.0	0.2	0.3	-0.1	0.0	0.6	0.3
42.7	14.3	13.9	14.1	14.0	13.9	13.7	14.0	14.7	14.5	-0.4	-0.3	-0.3	-0.4	-0.6	-0.3	0.3	0.1
45.9	13.1	13.1	13.3	12.9	13.0	13.3	13.0	13.4	13.6	0.1	0.2	-0.2	-0.1	0.2	-0.1	0.3	0.5
49.2	12.8	12.9	12.9	12.7	12.9	13.2	12.7	12.6	12.6	0.2	0.2	-0.1	0.1	0.4	0.0	-0.2	-0.1
52.5	13.9	13.4	13.3	13.9	13.5	14.0	13.9	14.1	13.3	-0.5	-0.6	0.0	-0.4	0.1	0.0	0.2	-0.6
55.8	12.5	12.3	12.2	12.3	12.6	13.0	12.5	12.4	12.6	-0.2	-0.3	-0.2	0.1	0.5	0.0	-0.1	0.1
59.1	13.6	13.6	13.7	13.6	17.0	18.0	16.7	15.9	16.1	0.0	0.0	0.0	3.4	4.4	3.1	2.3	2.4
62.3	13.2	13.2	13.5	13.3	13.6	13.9	13.5	14.1	14.0	-0.1	0.3	0.1	0.4	0.7	0.2	0.8	0.8
65.6	15.8	15.4	15.4	15.5	15.9	15.2	15.7	17.5	17.6	-0.4	-0.3	-0.2	0.1	-0.5	-0.1	1.7	1.9
68.9	13.4	13.3	13.1	13.6	13.7	13.6	13.6	13.5	13.4	-0.1	-0.3	0.2	0.3	0.2	0.3	0.1	0.0
72.2	12.7	12.3	12.5	12.4	12.5	13.1	13.2	13.7	15.5	-0.4	-0.2	-0.3	-0.2	0.4	0.5	1.0	2.8
75.5	13.9	14.1	13.4	13.8	13.7	13.5	13.8	13.9	18.6	0.2	-0.4	-0.1	-0.2	-0.3	-0.1	0.1	4.8
78.7	13.2	12.8	13.2	13.3	12.9	13.7	13.7	13.0	16.9	-0.4	0.0	0.1	-0.3	0.5	0.5	-0.2	3.7

Table 26. Headquarters Drywell – Increases in VWC (θ) ≥ 1.5% marked in yellow and orange for the synthetic storm event (neutron probe 2)

Neutron Probe 2																	
	Time Stamp (hr)									DELTA θ							
	0.0	2.5	4.7	6.6	20.6	25.8	29.7	43.8	77.4								
Depth (ft)	Volumetric Water Content (%)									2.5 - 0.0	4.7 - 0.0	6.6 - 0.0	20.6 - 0.0	25.8 - 0.0	29.7 - 0.0	43.8 - 0.0	77.4 - 0.0
3.3	13.3	11.5	11.4	11.2	11.1	11.0	11.2	11.1	11.2	-1.9	-2.0	-2.1	-2.2	-2.3	-2.1	-2.2	-2.1
6.6	12.8	17.9	17.9	18.1	17.8	17.3	17.3	17.3	17.1	5.1	5.1	5.3	5.1	4.5	4.5	4.6	4.3
9.8	12.3	12.3	11.8	11.7	12.2	12.3	12.1	12.2	12.5	0.0	-0.4	-0.5	-0.1	0.0	-0.2	-0.1	0.3
13.1	12.5	11.7	11.8	11.9	11.9	11.9	11.9	11.6	11.9	-0.7	-0.7	-0.6	-0.6	-0.6	-0.6	-0.9	-0.5
16.4	13.2	11.6	11.8	12.0	12.4	12.4	12.5	12.4	12.9	-1.5	-1.3	-1.2	-0.7	-0.7	-0.6	-0.8	-0.3
19.7	15.7	19.6	19.9	20.4	20.3	20.1	19.8	19.6	19.6	3.9	4.3	4.7	4.7	4.4	4.2	4.0	3.9
23.0	14.8	18.3	18.5	18.5	18.9	19.3	19.4	19.0	19.2	3.6	3.7	3.8	4.1	4.6	4.6	4.3	4.5
26.2	15.3	13.8	13.6	13.4	13.5	13.6	13.6	13.7	13.8	-1.5	-1.7	-1.9	-1.8	-1.7	-1.7	-1.6	-1.5
29.5	12.7	11.8	12.0	13.0	12.9	13.1	12.7	12.8	12.8	-0.9	-0.7	0.3	0.2	0.4	0.0	0.1	0.1
32.8	12.4	11.9	11.9	15.1	15.8	15.6	14.5	14.8	14.1	-0.5	-0.5	2.7	3.4	3.2	2.1	2.4	1.7
36.1	15.4	14.6	14.5	14.3	17.3	17.5	17.5	16.8	16.8	-0.8	-0.9	-1.1	1.9	2.1	2.1	1.4	1.4
39.4	14.1	13.7	13.4	13.5	14.3	14.2	14.2	14.5	14.4	-0.4	-0.7	-0.6	0.2	0.1	0.1	0.4	0.3
42.7	14.1	13.6	13.6	13.8	13.9	13.4	13.6	13.6	14.4	-0.5	-0.4	-0.2	-0.1	-0.7	-0.4	-0.4	0.4
45.9	13.8	14.0	14.1	13.8	14.4	14.2	14.1	14.0	14.2	0.2	0.3	0.0	0.6	0.4	0.3	0.2	0.4
49.2	13.9	12.4	12.3	12.1	12.5	11.7	12.3	12.2	12.4	-1.5	-1.6	-1.8	-1.4	-2.2	-1.6	-1.7	-1.5
52.5	14.4	14.3	14.6	14.5	14.8	14.3	14.6	14.7	14.6	0.0	0.2	0.1	0.4	-0.1	0.2	0.3	0.2
55.8	10.7	10.0	10.1	20.2	16.1	15.4	14.6	14.6	14.5	-0.7	-0.6	9.4	5.3	4.7	3.9	3.9	3.8
59.1	14.0	13.0	12.7	15.4	19.2	19.1	19.3	19.2	18.1	-0.9	-1.3	1.4	5.2	5.1	5.3	5.2	4.1
62.3	14.3	12.5	13.0	12.3	15.7	19.0	19.2	15.2	10.7	-1.8	-1.4	-2.1	1.3	4.7	4.9	0.8	-3.7
65.6	15.1	14.2	14.2	14.1	14.5	19.3	19.4	19.0	18.6	-0.9	-0.9	-1.0	-0.6	4.2	4.3	3.9	3.5
68.9	16.8	13.5	13.1	12.9	13.4	13.5	13.6	17.1	18.1	-3.3	-3.7	-3.8	-3.4	-3.3	-3.1	0.3	1.4
72.2	15.0	14.3	14.2	14.4	14.8	14.9	15.1	18.8	19.7	-0.7	-0.8	-0.6	-0.3	-0.1	0.1	3.8	4.7
75.5	18.1	14.8	15.0	14.5	15.2	15.5	15.5	17.6	19.7	-3.3	-3.1	-3.6	-2.9	-2.6	-2.6	-0.5	1.6
78.7	14.1	13.4	13.3	13.4	13.7	13.6	13.4	13.1	17.2	-0.8	-0.9	-0.7	-0.4	-0.6	-0.7	-1.0	3.1

Table 27. Headquarters Drywell – Increases in VWC (θ) ≥ 1.5% marked in yellow and orange for the synthetic storm event (neutron probe 3)

Neutron Probe 3																	
	Time Stamp (hr)									DELTA θ							
	0.0	2.5	4.7	6.6	20.6	25.8	29.7	43.8	77.4								
Depth (ft)	Volumetric Water Content (%)									2.5 - 0.0	4.7 - 0.0	6.6 - 0.0	20.6 - 0.0	25.8 - 0.0	29.7 - 0.0	43.8 - 0.0	77.4 - 0.0
3.3	11.0	13.2	13.3	13.5	13.2	13.1	13.3	12.8	13.1	2.2	2.3	2.5	2.2	2.1	2.3	1.8	2.1
6.6	18.0	12.7	12.8	12.7	12.4	12.8	12.7	12.6	12.1	-5.3	-5.2	-5.3	-5.6	-5.2	-5.3	-5.4	-5.9
9.8	12.0	12.3	12.7	12.3	12.4	12.6	12.1	12.0	12.6	0.2	0.6	0.3	0.4	0.5	0.1	0.0	0.6
13.1	11.8	12.0	12.4	12.2	12.2	12.0	11.9	12.4	12.1	0.2	0.6	0.4	0.4	0.3	0.2	0.6	0.4
16.4	12.0	13.4	13.7	13.3	13.7	13.8	13.4	13.6	13.6	1.4	1.7	1.4	1.7	1.8	1.4	1.7	1.6
19.7	13.4	16.9	20.4	20.5	20.3	20.3	19.9	19.5	19.2	3.5	7.0	7.1	6.9	6.9	6.5	6.0	5.7
23.0	18.7	14.5	18.1	18.1	18.0	18.0	18.1	17.6	17.9	-4.2	-0.5	-0.5	-0.7	-0.6	-0.5	-1.0	-0.7
26.2	13.5	14.9	15.6	15.1	17.1	16.0	16.5	16.7	16.1	1.3	2.1	1.6	3.5	2.4	2.9	3.2	2.6
29.5	12.5	15.9	19.7	19.3	16.3	16.5	15.9	16.5	16.0	3.5	7.2	6.8	3.8	4.1	3.4	4.0	3.5
32.8	11.5	12.7	19.0	18.9	17.6	17.2	17.2	17.0	16.6	1.2	7.5	7.4	6.1	5.7	5.7	5.5	5.1
36.1	14.4	14.9	18.9	19.9	19.5	19.8	19.4	18.7	17.9	0.6	4.6	5.5	5.1	5.4	5.1	4.3	3.5
39.4	13.6	14.2	14.4	14.0	15.7	15.0	15.5	15.5	15.4	0.5	0.8	0.4	2.1	1.4	1.9	1.9	1.7
42.7	13.5	13.9	14.1	13.9	13.9	14.6	14.4	14.6	15.2	0.4	0.7	0.4	0.5	1.1	0.9	1.1	1.7
45.9	14.2	14.1	13.8	13.9	14.0	14.1	13.9	14.0	14.5	-0.1	-0.4	-0.3	-0.2	-0.1	-0.3	-0.2	0.3
49.2	12.3	13.9	13.9	13.8	13.7	14.3	13.8	13.9	14.2	1.6	1.6	1.6	1.4	2.0	1.5	1.7	1.9
52.5	14.3	14.0	24.5	21.4	19.4	19.0	19.3	18.5	18.6	-0.3	10.2	7.2	5.2	4.7	5.1	4.2	4.4
55.8	10.3	10.7	19.9	20.2	17.0	16.2	16.6	16.0	16.3	0.4	9.6	9.9	6.6	5.9	6.3	5.7	5.9
59.1	12.5	14.1	16.9	19.5	17.9	17.9	17.6	16.9	15.9	1.6	4.4	7.0	5.4	5.4	5.1	4.4	3.4
62.3	12.9	14.1	14.4	18.3	18.2	18.0	18.0	18.0	17.7	1.2	1.5	5.4	5.4	5.2	5.2	5.2	4.8
65.6	14.1	15.1	15.8	15.6	17.1	17.3	17.4	17.3	17.2	1.0	1.7	1.6	3.1	3.2	3.4	3.2	3.1
68.9	13.2	16.6	16.7	16.6	17.2	17.4	17.2	17.7	17.3	3.4	3.5	3.4	4.0	4.2	4.0	4.5	4.1
72.2	14.4	15.6	15.3	15.2	15.9	16.2	16.7	19.9	20.1	1.2	1.0	0.8	1.5	1.8	2.3	5.5	5.7
75.5	14.5	18.1	17.6	16.9	17.8	17.5	18.1	20.1	20.1	3.6	3.1	2.4	3.3	3.0	3.6	5.7	5.6
78.7	13.2	14.7	14.6	14.5	14.5	14.5	14.1	16.7	16.9	1.4	1.3	1.2	1.2	1.3	0.9	3.4	3.7

A6.4 Van Nuys – Synthetic Storm Event

Data

Table 28. Van Nuys Drywell – VWC (θ) observations for the synthetic storm event (neutron probe 1)

Neutron Probe 1					
	Time Stamp (hr)				
	0.0	2.3	4.4	26.1	27.4
Depth (ft)	Volumetric Water Content (θ)				
3.3	22.6	22.6	22.9	22.8	23.1
6.6	23.3	22.9	23.5	23.4	23.4
9.8	22.2	22.5	22.3	22.2	22.3
13.1	21.7	21.7	21.5	21.5	21.6
16.4	20.2	20.1	20.5	20.0	20.4
19.7	20.6	21.1	20.8	21.2	21.4
23.0	19.7	20.7	21.0	21.3	20.9
26.2	19.2	20.8	20.9	21.7	21.2
29.5	21.5	21.5	21.4	22.0	21.7
32.8	21.9	21.7	22.5	22.4	22.5
36.1	22.4	22.5	22.6	24.0	22.4
39.4	23.5	23.9	24.1	19.9	23.6
42.7	13.9	19.6	19.5	19.6	19.1

Data Analysis – Probe 1

Table 29. Van Nuys Drywell – Increases in VWC (θ) ≥ 1.5% marked in yellow and orange for the synthetic storm event (neutron probe 1)

Neutron Probe 1									
	Time Stamp (hr)					DELTA θ			
	0.0	2.3	4.4	26.1	27.4				
Depth (ft)	Volumetric Water Content (θ)					2.3 - 0.0	4.4 - 0.0	26.1 - 0.0	27.4 - 0.0
3.3	22.6	22.6	22.9	22.8	23.1	0.0	0.3	0.2	0.5
6.6	23.3	22.9	23.5	23.4	23.4	-0.4	0.2	0.1	0.1
9.8	22.2	22.5	22.3	22.2	22.3	0.3	0.1	0.0	0.1
13.1	21.7	21.7	21.5	21.5	21.6	0.0	-0.2	-0.2	-0.1
16.4	20.2	20.1	20.5	20.0	20.4	-0.2	0.2	-0.2	0.1
19.7	20.6	21.1	20.8	21.2	21.4	0.4	0.1	0.6	0.8
23.0	19.7	20.7	21.0	21.3	20.9	1.0	1.3	1.7	1.2
26.2	19.2	20.8	20.9	21.7	21.2	1.6	1.7	2.5	1.9
29.5	21.5	21.5	21.4	22.0	21.7	0.0	-0.1	0.5	0.2
32.8	21.9	21.7	22.5	22.4	22.5	-0.3	0.6	0.4	0.6
36.1	22.4	22.5	22.6	24.0	22.4	0.1	0.2	1.6	0.0
39.4	23.5	23.9	24.1	19.9	23.6	0.4	0.6	-3.6	0.2
42.7	13.9	19.6	19.5	19.6	19.1	5.7	5.5	5.6	5.2

Data

Table 30. Van Nuys Drywell – VWC (θ) observations for the synthetic storm event (neutron probe 1)

Neutron Probe 2					
	Time Stamp (hr)				
	0.0	2.3	4.4	26.1	27.4
Depth (ft)	Volumetric Water Content (θ)				
3.3	23.5	23.6	23.5	24.0	23.3
6.6	23.2	23.2	23.3	23.2	23.5
9.8	22.5	22.3	22.1	22.3	22.2
13.1	22.4	21.8	22.2	22.0	22.8
16.4	22.9	22.4	22.9	23.4	22.8
19.7	23.1	23.1	23.3	22.9	23.5
23.0	23.8	24.2	23.5	24.0	24.2
26.2	24.3	23.8	24.7	23.4	24.3
29.5	23.6	23.7	23.9	23.6	24.2
32.8	23.5	23.8	23.4	23.5	23.1
36.1	23.1	23.2	23.3	23.5	23.2
39.4	22.1	22.6	22.5	22.0	22.2
42.7	21.7	22.2	21.8	21.0	22.0
45.9	20.4	20.1	21.4	21.7	21.4
49.2	22.7	21.9	23.2	22.4	22.4
52.5	23.0	23.2	23.3	22.9	23.4
55.8	22.7	22.7	22.5	22.6	22.7
59.1	21.5	21.3	21.4	21.3	21.8
62.3	20.1	20.1	20.0	20.4	20.3
65.6	21.9	21.9	22.2	21.9	22.3
68.9	12.1	12.3	12.5	12.2	12.1
72.2	16.1	15.6	15.9	16.1	15.8
75.5	16.3	16.4	16.7	17.0	16.9

Data Analysis – Probe 2

Table 31. Van Nuys Drywell – Increases in VWC (θ) ≥ 1.5% marked in yellow and orange for the synthetic storm event (neutron probe 2)

Neutron Probe 2									
	Time Stamp (hr)					DELTA θ			
	0.0	2.3	4.4	26.1	27.4				
Depth (ft)	Volumetric Water Content (θ)					2.3 - 0.0	4.4 - 0.0	26.1 - 0.0	27.4 - 0.0
3.3	23.5	23.6	23.5	24.0	23.3	0.1	0.0	0.5	-0.2
6.6	23.2	23.2	23.3	23.2	23.5	0.1	0.1	0.0	0.3
9.8	22.5	22.3	22.1	22.3	22.2	-0.2	-0.4	-0.2	-0.3
13.1	22.4	21.8	22.2	22.0	22.8	-0.6	-0.2	-0.4	0.4
16.4	22.9	22.4	22.9	23.4	22.8	-0.5	0.0	0.5	-0.1
19.7	23.1	23.1	23.3	22.9	23.5	0.0	0.2	-0.2	0.5
23.0	23.8	24.2	23.5	24.0	24.2	0.4	-0.3	0.2	0.4
26.2	24.3	23.8	24.7	23.4	24.3	-0.5	0.4	-0.8	0.0
29.5	23.6	23.7	23.9	23.6	24.2	0.1	0.3	0.0	0.6
32.8	23.5	23.8	23.4	23.5	23.1	0.3	-0.2	0.0	-0.4
36.1	23.1	23.2	23.3	23.5	23.2	0.1	0.2	0.3	0.1
39.4	22.1	22.6	22.5	22.0	22.2	0.4	0.4	-0.1	0.1
42.7	21.7	22.2	21.8	21.0	22.0	0.5	0.1	-0.7	0.4
45.9	20.4	20.1	21.4	21.7	21.4	-0.3	1.0	1.3	1.0
49.2	22.7	21.9	23.2	22.4	22.4	-0.8	0.5	-0.3	-0.4
52.5	23.0	23.2	23.3	22.9	23.4	0.2	0.3	-0.1	0.4
55.8	22.7	22.7	22.5	22.6	22.7	0.0	-0.2	-0.1	0.0
59.1	21.5	21.3	21.4	21.3	21.8	-0.2	-0.1	-0.2	0.3
62.3	20.1	20.1	20.0	20.4	20.3	0.0	-0.1	0.3	0.2
65.6	21.9	21.9	22.2	21.9	22.3	0.0	0.3	0.0	0.5
68.9	12.1	12.3	12.5	12.2	12.1	0.2	0.4	0.1	0.0
72.2	16.1	15.6	15.9	16.1	15.8	-0.4	-0.1	0.0	-0.2
75.5	16.3	16.4	16.7	17.0	16.9	0.1	0.4	0.7	0.6

A7. VS2DI Model Output – Observation Points

A7.1 Rosemead Bioswale — Synthetic Storm 1

TIME, hour	NODE	XR, ft	Z, ft	VZ	TIME, hour	NODE	XR, ft	Z, ft	VZ
0.50	1283	7.38	3.25	2.06E-26	1.50	1509	8.13	3.75	1.06E-01
1.00	1283	7.38	3.25	6.28E-05	2.00	1509	8.13	3.75	6.17E-01
1.50	1283	7.38	3.25	1.62E+00	0.50	1510	8.13	4.25	0.00E+00
2.00	1283	7.38	3.25	8.01E-01	1.00	1510	8.13	4.25	0.00E+00
2.50	1283	7.38	3.25	7.34E-01	1.50	1510	8.13	4.25	1.04E-06
3.00	1283	7.38	3.25	7.29E-01	2.00	1510	8.13	4.25	7.06E-02
3.50	1283	7.38	3.25	6.98E-01	2.50	1510	8.13	4.25	2.72E-01
4.00	1283	7.38	3.25	6.89E-01	3.00	1510	8.13	4.25	4.09E-01
0.50	1284	7.38	3.75	3.24E-34	3.50	1510	8.13	4.25	3.77E-01
1.00	1284	7.38	3.75	4.16E-23	4.00	1510	8.13	4.25	3.52E-01
1.50	1284	7.38	3.75	1.46E-01	0.50	1658	8.63	3.25	3.74E-27
2.00	1284	7.38	3.75	5.96E-01	1.00	1658	8.63	3.25	7.09E-06
2.50	1284	7.38	3.75	4.81E-01	1.50	1658	8.63	3.25	1.74E+00
3.00	1284	7.38	3.75	4.50E-01	2.00	1658	8.63	3.25	8.17E-01
3.50	1284	7.38	3.75	4.18E-01	2.50	1658	8.63	3.25	7.32E-01
4.00	1284	7.38	3.75	4.11E-01	3.00	1658	8.63	3.25	7.26E-01
0.50	1285	7.38	4.25	0.00E+00	3.50	1658	8.63	3.25	6.96E-01
1.00	1285	7.38	4.25	0.00E+00	4.00	1658	8.63	3.25	6.87E-01
1.50	1285	7.38	4.25	1.96E-10	0.50	1659	8.63	3.75	3.24E-34
2.00	1285	7.38	4.25	5.72E-02	1.00	1659	8.63	3.75	3.23E-24
2.50	1285	7.38	4.25	2.24E-01	1.50	1659	8.63	3.75	1.66E-01
3.00	1285	7.38	4.25	3.68E-01	2.00	1659	8.63	3.75	6.06E-01
3.50	1285	7.38	4.25	3.46E-01	2.50	1659	8.63	3.75	4.83E-01
4.00	1285	7.38	4.25	3.26E-01	3.00	1659	8.63	3.75	4.52E-01
0.50	1508	8.13	3.25	8.50E-26	3.50	1659	8.63	3.75	4.19E-01
1.00	1508	8.13	3.25	4.49E-03	4.00	1659	8.63	3.75	4.12E-01
1.50	1508	8.13	3.25	1.49E+00	0.50	1660	8.63	4.25	0.00E+00
2.00	1508	8.13	3.25	6.34E-01	1.00	1660	8.63	4.25	0.00E+00
2.50	1508	8.13	3.25	5.97E-01	1.50	1660	8.63	4.25	1.23E-13
3.00	1508	8.13	3.25	5.82E-01	2.00	1660	8.63	4.25	5.40E-02
3.50	1508	8.13	3.25	5.51E-01	2.50	1660	8.63	4.25	2.21E-01
4.00	1508	8.13	3.25	5.44E-01	3.00	1660	8.63	4.25	3.70E-01
0.50	1509	8.13	3.75	3.24E-34	3.50	1660	8.63	4.25	3.47E-01
1.00	1509	8.13	3.75	6.66E-21	4.00	1660	8.63	4.25	3.26E-01

A7.2 Rosemead Bioswale — Synthetic Storm 2

TIME, hour	NODE	XR, ft	Z, ft	VZ	TIME, hour	NODE	XR, ft	Z, ft	VZ
0.50	1283	7.38	3.25	1.82E-22	3.01	1509	8.13	3.75	4.35E-01
1.00	1283	7.38	3.25	1.23E+00	3.51	1509	8.13	3.75	4.20E-01
1.51	1283	7.38	3.25	9.02E-01	4.01	1509	8.13	3.75	4.10E-01
2.01	1283	7.38	3.25	7.98E-01	4.50	1509	8.13	3.75	4.00E-01
2.51	1283	7.38	3.25	7.60E-01	1.00	1510	8.13	4.25	1.73E-01
3.01	1283	7.38	3.25	7.28E-01	1.51	1510	8.13	4.25	5.06E-01
3.51	1283	7.38	3.25	7.05E-01	2.01	1510	8.13	4.25	4.28E-01
4.01	1283	7.38	3.25	6.88E-01	2.51	1510	8.13	4.25	3.87E-01
4.50	1283	7.38	3.25	6.73E-01	3.01	1510	8.13	4.25	3.49E-01
0.50	1284	7.38	3.75	3.24E-34	3.51	1510	8.13	4.25	3.35E-01
1.00	1284	7.38	3.75	9.00E-01	4.01	1510	8.13	4.25	3.27E-01
1.51	1284	7.38	3.75	5.90E-01	4.50	1510	8.13	4.25	3.18E-01
2.01	1284	7.38	3.75	4.77E-01	0.50	1658	8.63	3.25	2.75E-17
2.51	1284	7.38	3.75	4.54E-01	1.00	1658	8.63	3.25	1.20E+00
3.01	1284	7.38	3.75	4.32E-01	1.51	1658	8.63	3.25	8.77E-01
3.51	1284	7.38	3.75	4.16E-01	2.01	1658	8.63	3.25	7.84E-01
4.01	1284	7.38	3.75	4.06E-01	2.51	1658	8.63	3.25	7.52E-01
4.50	1284	7.38	3.75	3.97E-01	3.01	1658	8.63	3.25	7.21E-01
0.50	1285	7.38	4.25	0.00E+00	3.51	1658	8.63	3.25	6.99E-01
1.00	1285	7.38	4.25	8.58E-02	4.01	1658	8.63	3.25	6.83E-01
1.51	1285	7.38	4.25	4.42E-01	4.50	1658	8.63	3.25	6.69E-01
2.01	1285	7.38	4.25	4.06E-01	0.50	1659	8.63	3.75	5.40E-34
2.51	1285	7.38	4.25	3.63E-01	1.00	1659	8.63	3.75	7.85E-01
3.01	1285	7.38	4.25	3.30E-01	1.51	1659	8.63	3.75	5.53E-01
3.51	1285	7.38	4.25	3.13E-01	2.01	1659	8.63	3.75	4.71E-01
4.01	1285	7.38	4.25	3.04E-01	2.51	1659	8.63	3.75	4.51E-01
4.50	1285	7.38	4.25	2.97E-01	3.01	1659	8.63	3.75	4.30E-01
0.50	1508	8.13	3.25	2.62E-17	3.51	1659	8.63	3.75	4.15E-01
1.00	1508	8.13	3.25	9.20E-01	4.01	1659	8.63	3.75	4.05E-01
1.51	1508	8.13	3.25	7.15E-01	4.50	1659	8.63	3.75	3.96E-01
2.01	1508	8.13	3.25	6.22E-01	0.50	1660	8.63	4.25	0.00E+00
2.51	1508	8.13	3.25	5.97E-01	1.00	1660	8.63	4.25	1.73E-01
3.01	1508	8.13	3.25	5.68E-01	1.51	1660	8.63	4.25	4.52E-01
3.51	1508	8.13	3.25	5.49E-01	2.01	1660	8.63	4.25	3.91E-01
4.01	1508	8.13	3.25	5.36E-01	2.51	1660	8.63	4.25	3.58E-01
4.50	1508	8.13	3.25	5.24E-01	3.01	1660	8.63	4.25	3.27E-01
0.50	1509	8.13	3.75	5.40E-34	3.51	1660	8.63	4.25	3.12E-01
1.00	1509	8.13	3.75	8.79E-01	4.01	1660	8.63	4.25	3.04E-01

1.51	1509	8.13	3.75	5.61E-01	4.50	1660	8.63	4.25	2.97E-01
2.01	1509	8.13	3.75	4.78E-01					
2.51	1509	8.13	3.75	4.60E-01					

A7.3 Headquarters Drywell — Synthetic Storm

TIME, hour	NODE	XR, ft	Z, ft	VZ[1]	TIME, hour	NODE	XR, ft	Z, ft	VZ
2.00	45994	92.75	24.25	0.00E+00	2.00	53650	108.25	23.75	2.33E+06
2.50	45994	92.75	24.25	0.00E+00	2.50	53650	108.25	23.75	9.56E+05
3.00	45994	92.75	24.25	0.00E+00	3.00	53650	108.25	23.75	5.40E+05
3.50	45994	92.75	24.25	0.00E+00	3.50	53650	108.25	23.75	6.03E+05
4.00	45994	92.75	24.25	0.00E+00	4.00	53650	108.25	23.75	5.49E+05
4.50	45994	92.75	24.25	0.00E+00	4.50	53650	108.25	23.75	8.18E+05
5.00	45994	92.75	24.25	0.00E+00	5.00	53650	108.25	23.75	6.49E+05
5.50	45994	92.75	24.25	0.00E+00	5.50	53650	108.25	23.75	7.94E+05
2.00	45995	92.75	24.75	-9.05E-01	2.00	53651	108.25	24.25	2.04E+06
2.50	45995	92.75	24.75	-1.64E+00	2.50	53651	108.25	24.25	9.95E+05
3.00	45995	92.75	24.75	-7.93E-01	3.00	53651	108.25	24.25	5.26E+05
3.50	45995	92.75	24.75	-5.02E-01	3.50	53651	108.25	24.25	6.13E+05
4.00	45995	92.75	24.75	-3.75E-01	4.00	53651	108.25	24.25	7.13E+05
4.50	45995	92.75	24.75	-2.63E-01	4.50	53651	108.25	24.25	9.11E+05
5.00	45995	92.75	24.75	-8.80E-02	5.00	53651	108.25	24.25	6.74E+05
5.50	45995	92.75	24.75	-2.35E-03	5.50	53651	108.25	24.25	7.93E+05
2.00	45996	92.75	25.25	5.49E-01	2.00	53652	108.25	24.75	4.76E+06
2.50	45996	92.75	25.25	3.90E-01	2.50	53652	108.25	24.75	1.28E+06
3.00	45996	92.75	25.25	1.76E-01	3.00	53652	108.25	24.75	5.72E+05
3.50	45996	92.75	25.25	1.66E-01	3.50	53652	108.25	24.75	6.85E+05
4.00	45996	92.75	25.25	1.73E-01	4.00	53652	108.25	24.75	8.10E+05
4.50	45996	92.75	25.25	1.81E-01	4.50	53652	108.25	24.75	1.00E+06
5.00	45996	92.75	25.25	2.02E-01	5.00	53652	108.25	24.75	7.20E+05
5.50	45996	92.75	25.25	2.07E-01	5.50	53652	108.25	24.75	8.18E+05
2.00	46735	94.25	24.25	0.00E+00	2.00	54012	108.75	81.25	0.00E+00
2.50	46735	94.25	24.25	0.00E+00	2.50	54012	108.75	81.25	0.00E+00
3.00	46735	94.25	24.25	0.00E+00	3.00	54012	108.75	81.25	0.00E+00
3.50	46735	94.25	24.25	0.00E+00	3.50	54012	108.75	81.25	0.00E+00
4.00	46735	94.25	24.25	0.00E+00	4.00	54012	108.75	81.25	0.00E+00
4.50	46735	94.25	24.25	0.00E+00	4.50	54012	108.75	81.25	0.00E+00
5.00	46735	94.25	24.25	0.00E+00	5.00	54012	108.75	81.25	0.00E+00
5.50	46735	94.25	24.25	0.00E+00	5.50	54012	108.75	81.25	0.00E+00
2.00	46736	94.25	24.75	8.05E-01	2.00	54013	108.75	81.75	0.00E+00
2.50	46736	94.25	24.75	-6.49E-02	2.50	54013	108.75	81.75	-1.45E+01
3.00	46736	94.25	24.75	4.68E-02	3.00	54013	108.75	81.75	-9.31E+00
3.50	46736	94.25	24.75	9.98E-02	3.50	54013	108.75	81.75	-7.10E+00

4.00	46736	94.25	24.75	1.24E-01	4.00	54013	108.75	81.75	-6.01E+00
4.50	46736	94.25	24.75	1.45E-01	4.50	54013	108.75	81.75	-5.03E+00
5.00	46736	94.25	24.75	1.79E-01	5.00	54013	108.75	81.75	-3.81E+00
5.50	46736	94.25	24.75	2.03E-01	5.50	54013	108.75	81.75	-3.04E+00
2.00	46737	94.25	25.25	5.01E-01	2.00	54014	108.75	82.25	0.00E+00
2.50	46737	94.25	25.25	4.21E-01	2.50	54014	108.75	82.25	4.57E+00
3.00	46737	94.25	25.25	2.41E-01	3.00	54014	108.75	82.25	-1.98E-01
3.50	46737	94.25	25.25	2.26E-01	3.50	54014	108.75	82.25	-3.06E-01
4.00	46737	94.25	25.25	2.36E-01	4.00	54014	108.75	82.25	-2.49E-01
4.50	46737	94.25	25.25	2.33E-01	4.50	54014	108.75	82.25	-2.07E-01
5.00	46737	94.25	25.25	2.42E-01	5.00	54014	108.75	82.25	-2.91E-01
5.50	46737	94.25	25.25	2.41E-01	5.50	54014	108.75	82.25	-1.94E-01
2.00	47476	95.75	24.25	0.00E+00	2.00	54259	109.25	81.25	0.00E+00
2.50	47476	95.75	24.25	0.00E+00	2.50	54259	109.25	81.25	0.00E+00
3.00	47476	95.75	24.25	0.00E+00	3.00	54259	109.25	81.25	0.00E+00
3.50	47476	95.75	24.25	0.00E+00	3.50	54259	109.25	81.25	0.00E+00
4.00	47476	95.75	24.25	0.00E+00	4.00	54259	109.25	81.25	0.00E+00
4.50	47476	95.75	24.25	0.00E+00	4.50	54259	109.25	81.25	0.00E+00
5.00	47476	95.75	24.25	0.00E+00	5.00	54259	109.25	81.25	0.00E+00
5.50	47476	95.75	24.25	0.00E+00	5.50	54259	109.25	81.25	0.00E+00
2.00	47477	95.75	24.75	1.02E+00	2.00	54260	109.25	81.75	0.00E+00
2.50	47477	95.75	24.75	4.23E-01	2.50	54260	109.25	81.75	-1.48E+01
3.00	47477	95.75	24.75	3.93E-01	3.00	54260	109.25	81.75	-7.27E+00
3.50	47477	95.75	24.75	3.90E-01	3.50	54260	109.25	81.75	-5.86E+00
4.00	47477	95.75	24.75	3.76E-01	4.00	54260	109.25	81.75	-5.26E+00
4.50	47477	95.75	24.75	3.58E-01	4.50	54260	109.25	81.75	-4.64E+00
5.00	47477	95.75	24.75	3.35E-01	5.00	54260	109.25	81.75	-3.56E+00
5.50	47477	95.75	24.75	3.26E-01	5.50	54260	109.25	81.75	-2.77E+00
2.00	47478	95.75	25.25	1.45E-01	2.00	54261	109.25	82.25	0.00E+00
2.50	47478	95.75	25.25	5.50E-01	2.50	54261	109.25	82.25	5.10E+00
3.00	47478	95.75	25.25	5.65E-01	3.00	54261	109.25	82.25	-9.79E-01
3.50	47478	95.75	25.25	4.54E-01	3.50	54261	109.25	82.25	-6.98E-01
4.00	47478	95.75	25.25	3.96E-01	4.00	54261	109.25	82.25	-4.37E-01

4.50	47478	95.75	25.25	3.47E-01	4.50	54261	109.25	82.25	-2.72E-01
5.00	47478	95.75	25.25	3.21E-01	5.00	54261	109.25	82.25	-3.23E-01
5.50	47478	95.75	25.25	3.12E-01	5.50	54261	109.25	82.25	-2.36E-01
2.00	48217	97.25	24.25	0.00E+00	2.00	54391	109.75	23.75	2.24E+06
2.50	48217	97.25	24.25	0.00E+00	2.50	54391	109.75	23.75	9.24E+05
3.00	48217	97.25	24.25	0.00E+00	3.00	54391	109.75	23.75	4.28E+05
3.50	48217	97.25	24.25	0.00E+00	3.50	54391	109.75	23.75	4.73E+05
4.00	48217	97.25	24.25	0.00E+00	4.00	54391	109.75	23.75	4.45E+05
4.50	48217	97.25	24.25	0.00E+00	4.50	54391	109.75	23.75	7.33E+05
5.00	48217	97.25	24.25	0.00E+00	5.00	54391	109.75	23.75	5.94E+05
5.50	48217	97.25	24.25	0.00E+00	5.50	54391	109.75	23.75	7.36E+05
2.00	48218	97.25	24.75	1.02E+00	2.00	54392	109.75	24.25	2.35E+06
2.50	48218	97.25	24.75	6.02E-01	2.50	54392	109.75	24.25	1.01E+06
3.00	48218	97.25	24.75	5.75E-01	3.00	54392	109.75	24.25	4.47E+05
3.50	48218	97.25	24.75	5.59E-01	3.50	54392	109.75	24.25	5.13E+05
4.00	48218	97.25	24.75	5.46E-01	4.00	54392	109.75	24.25	6.28E+05
4.50	48218	97.25	24.75	5.43E-01	4.50	54392	109.75	24.25	8.33E+05
5.00	48218	97.25	24.75	5.06E-01	5.00	54392	109.75	24.25	6.29E+05
5.50	48218	97.25	24.75	4.74E-01	5.50	54392	109.75	24.25	7.45E+05
2.00	48219	97.25	25.25	1.43E-01	2.00	54393	109.75	24.75	4.79E+06
2.50	48219	97.25	25.25	4.49E-01	2.50	54393	109.75	24.75	1.26E+06
3.00	48219	97.25	25.25	4.38E-01	3.00	54393	109.75	24.75	5.18E+05
3.50	48219	97.25	25.25	4.48E-01	3.50	54393	109.75	24.75	6.15E+05
4.00	48219	97.25	25.25	4.90E-01	4.00	54393	109.75	24.75	7.54E+05
4.50	48219	97.25	25.25	5.21E-01	4.50	54393	109.75	24.75	9.43E+05
5.00	48219	97.25	25.25	3.82E-01	5.00	54393	109.75	24.75	6.94E+05
5.50	48219	97.25	25.25	3.38E-01	5.50	54393	109.75	24.75	7.80E+05
2.00	52909	106.75	23.75	2.37E-01	2.00	55132	111.25	23.75	-4.12E-02
2.50	52909	106.75	23.75	1.36E-01	2.50	55132	111.25	23.75	-5.64E-01
3.00	52909	106.75	23.75	8.59E-02	3.00	55132	111.25	23.75	-8.54E-01
3.50	52909	106.75	23.75	8.56E-02	3.50	55132	111.25	23.75	-8.82E-01
4.00	52909	106.75	23.75	7.42E-02	4.00	55132	111.25	23.75	-9.00E-01
4.50	52909	106.75	23.75	8.64E-02	4.50	55132	111.25	23.75	-8.90E-01
5.00	52909	106.75	23.75	9.17E-02	5.00	55132	111.25	23.75	-4.23E-01
5.50	52909	106.75	23.75	1.17E-01	5.50	55132	111.25	23.75	-1.93E-01
2.00	52910	106.75	24.25	5.00E-01	2.00	55133	111.25	24.25	1.25E+00
2.50	52910	106.75	24.25	1.67E-01	2.50	55133	111.25	24.25	4.12E-01
3.00	52910	106.75	24.25	1.03E-01	3.00	55133	111.25	24.25	2.45E-01
3.50	52910	106.75	24.25	1.13E-01	3.50	55133	111.25	24.25	2.67E-01
4.00	52910	106.75	24.25	1.21E-01	4.00	55133	111.25	24.25	2.73E-01
4.50	52910	106.75	24.25	1.34E-01	4.50	55133	111.25	24.25	2.88E-01

5.00	52910	106.75	24.25	9.83E-02	5.00	55133	111.25	24.25	9.39E-02
5.50	52910	106.75	24.25	9.94E-02	5.50	55133	111.25	24.25	1.23E-01
2.00	52911	106.75	24.75	9.79E-01	2.00	55134	111.25	24.75	3.48E+00
2.50	52911	106.75	24.75	2.84E-01	2.50	55134	111.25	24.75	9.76E-01
3.00	52911	106.75	24.75	9.07E-02	3.00	55134	111.25	24.75	5.63E-01
3.50	52911	106.75	24.75	9.75E-02	3.50	55134	111.25	24.75	4.36E-01
4.00	52911	106.75	24.75	1.18E-01	4.00	55134	111.25	24.75	3.76E-01
4.50	52911	106.75	24.75	1.29E-01	4.50	55134	111.25	24.75	3.55E-01
5.00	52911	106.75	24.75	9.65E-02	5.00	55134	111.25	24.75	2.34E-01
5.50	52911	106.75	24.75	9.26E-02	5.50	55134	111.25	24.75	1.57E-01

1The significantly large velocities shown here likely represent specified-flux boundary condition values expressed in the model's output units rather than actual Darcy velocities in the soil.

A7.4 Van Nuys Drywell — Synthetic Storm

TIME, hour	NODE	XR, ft	Z, ft	VZ	TIME, hour	NODE	XR, ft	Z, ft	VZ
0.50	238	0.25	40	-1.6E-29	3.06	395	0.75	41	6.743955
1.00	238	0.25	40	14.72907	3.50	395	0.75	41	1.618496
1.53	238	0.25	40	11.23817	4.00	395	0.75	41	12.06789
2.03	238	0.25	40	7.210851	0.50	396	0.75	41	-3.4E-31
2.50	238	0.25	40	9.137764	1.00	396	0.75	41	9.180255
3.06	238	0.25	40	8.427577	1.53	396	0.75	41	10.45746
3.50	238	0.25	40	1.917048	2.03	396	0.75	41	5.579147
4.00	238	0.25	40	14.41133	2.50	396	0.75	41	6.586656
0.50	239	0.25	41	-1.1E-31	3.06	396	0.75	41	4.904299
1.00	239	0.25	41	18.3077	3.50	396	0.75	41	1.328365
1.53	239	0.25	41	10.45519	4.00	396	0.75	41	9.936192
2.03	239	0.25	41	6.033628	0.50	550	1.25	40	-1.4E-29
2.50	239	0.25	41	7.529279	1.00	550	1.25	40	20.37763
3.06	239	0.25	41	6.592101	1.53	550	1.25	40	14.1794
3.50	239	0.25	41	1.562315	2.03	550	1.25	40	8.799317
4.00	239	0.25	41	11.67936	2.50	550	1.25	40	11.30946
0.50	240	0.25	41	-3.4E-31	3.06	550	1.25	40	10.86142
1.00	240	0.25	41	6.91555	3.50	550	1.25	40	2.453796
1.53	240	0.25	41	10.36118	4.00	550	1.25	40	18.05097
2.03	240	0.25	41	5.541155	0.50	551	1.25	41	0
2.50	240	0.25	41	6.59384	1.00	551	1.25	41	14.72146
3.06	240	0.25	41	4.949914	1.53	551	1.25	41	11.35882
3.50	240	0.25	41	1.32577	2.03	551	1.25	41	6.630165
4.00	240	0.25	41	9.906175	2.50	551	1.25	41	8.146671
0.50	394	0.75	40	-8.2E-30	3.06	551	1.25	41	6.969804
1.00	394	0.75	40	19.56361	3.50	551	1.25	41	1.720529

1.53	394	0.75	40	12.02828	4.00	551	1.25	41	12.79214
2.03	394	0.75	40	7.635014	0.50	552	1.25	41	-1.1E-31
2.50	394	0.75	40	9.703738	1.00	552	1.25	41	8.618687
3.06	394	0.75	40	9.097929	1.53	552	1.25	41	10.37442
3.50	394	0.75	40	2.057634	2.03	552	1.25	41	5.604995
4.00	394	0.75	40	15.37911	2.50	552	1.25	41	6.481921
0.50	395	0.75	41	3.2E-31	3.06	552	1.25	41	4.725143
1.00	395	0.75	41	20.94415	3.50	552	1.25	41	1.309648
1.53	395	0.75	41	10.83425	4.00	552	1.25	41	9.850943
2.03	395	0.75	41	6.242367					
2.50	395	0.75	41	7.747911					