

## **One-dimensional model to evaluate the hydraulic capacity of a full depth permeable pavement for stormwater management**

Un modèle unidimensionnel pour évaluer la capacité hydraulique d'une chaussée poreuse pour la gestion des eaux pluviales

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### **RÉSUMÉ**

La collecte et le traitement des eaux de ruissellement est désormais une composante essentielle de la conception des routes aux États-Unis, dans les pays européens et dans d'autres parties du monde. L'une des alternatives possibles pour gérer les eaux de ruissellement tout en protégeant l'environnement est l'utilisation des chaussées perméables en profondeur, capables de supporter une charge élevée et de contenir un grand volume dans les espaces vides du matériau. Ce document explore l'utilisation d'un modèle d'infiltration unidimensionnel pour déterminer l'épaisseur de la couche granulaire perméable nécessaire pour infiltrer le volume de ruissellement d'une pluie sur une période de récurrence de moins de 30 ans. De nombreuses simulations ont été effectuées pour trois régions climatiques de Californie, deux types de chaussées perméables (sur la chaussée entière ou sur les accotements uniquement) et deux épaisseurs de couche granulaire. Les résultats des simulations ont montré que pour la chaussée entière, une épaisseur d'environ 600 mm de couche granulaire était nécessaire afin d'infiltrer le volume de ruissellement et d'éviter tout débordement. Cette estimation préliminaire de l'épaisseur est raisonnable, puisque dans cette simulation, le sol environnant était constitué d'argile compactée ayant une perméabilité minimale. D'autres résultats indiquent également que lorsque seuls les accotements sont perméables, une épaisseur supérieure à 600mm ou des accotements plus larges sont nécessaires pour infiltrer toutes les eaux de ruissellement, sans débordement.

### **ABSTRACT**

Stormwater runoff collection and treatment is now an essential and integrated component of highway design in the U.S., European countries and other parts of the world. Transportation agencies are searching for cost effective ways to manage the runoff while protecting the environment. One potential and alternative way to deal with large volumes of highway runoff is through full depth permeable pavement design. To accomplish this objective, the pavement must support heavy load and traffic while retaining the runoff volume within the pavement's void spaces. This paper explores the use of a one dimensional infiltration model to determine the thickness of the permeable granule layer needed to capture the runoff volume under 30-year storm events. Numerous simulations were performed using three climate regions in California, two full depth permeable pavement structures (drive way or shoulders only) and two permeable gravel thicknesses. The simulation results showed that a thickness of about 600mm permeable granular base layer is needed in order to capture the entire storm volume and preventing overflow. This preliminary thickness estimation is conservative since the sub-base soil was made out of compacted clay with minimum permeability. The simulation results also indicate that where only the shoulder is permeable, 600mm thickness of granular material is not sufficient and a higher thickness or wider shoulder is needed to capture all stormwater runoff without excess water.

### **KEYWORDS**

Full depth permeable pavement, highway, hydraulic conductivity, Infiltration modelling, stormwater

## 1. INTRODUCTION

### 1.1. Background

Due to stringent water quality criteria in the U.S. and other parts of the world, stormwater runoff management is now an integrated part of highway design and maintenance program. Transportation agencies are constantly searching for the most practical and economical method to collect and treat highway runoff before discharging it to receiving waters. Many best management practices (BMPs) have been constructed and their potential use for stormwater runoff treatment has been investigated. In general, the constructed BMPs are expensive and in some cases require extensive maintenance. Permeable pavements on highways are an alternative method that may be used as BMP in order to decrease the quantity of stormwater runoff and reduce pollutants mass loading to receiving waters.

Compared to conventional impermeable pavements, fully-permeable pavement structures, have the ability to store water inside their structure in a aggregate base and subbase soil layer that collectively can be called as “reservoir base.” Alternatively, the drive-way can be impermeable and only the shoulders can be constructed as full depth permeable pavement. Both asphalt and concrete permeable pavements can be used as top permeable layer (Collins et al, 2006). The aggregate layer alone can have the capacity to store approximately one-fourth to one-half of its height with water, depending on the size of stone that is used to create the reservoir (NAPA, 2003). The pavement and subgrade layers can capture and/or treatment of oil and grease, heavy metals, suspended solids by the voids in the pavement (Ferguson et al., 2006; Fach and Geiger, 2005; Briggs et al., 2005).

When water permeate through the pavement, one question arise and that is weather or not pavement themselves generate any pollution. To address this question, Kayhanian et al (2009) recently performed one controoled laboratory study to evaluate the water quality of leachate produced from 12 different pavement mix types. The results of the study showed that except chromium and vanadiumm, the the concentration of all other organic and inorganic pollutants (metals, petrolum hydrocarbons, total P and N, PAHs) generated from the pavement itself is negligible and are not considered as a water quality concern. Nevertheless, the water quality benefits of permeable pavements are suspected to degrade as a function of time without proper maintenance of the surface course (Kuang and Sansalone, 2006).

Most full depth permeable pavement are aplyed to parking lots where the traffic and load are nor havey compared to highways. Application of a full depth permeable pavement under heavy load and traffic require the knowledge of structural stability of pavement as well as the hydraulic reservoir capacity. While minimum depth may be needed from structural point of view, this minimum depth may not be sufficient to capture and store major storm event rainfall volume. Equally important, there may be a minimum depth required to capture stormwater volume, however, it may not be sufficient from structural stability. Therefore, the optimum full depth permeable pavement will be designed when both structurll and hydraulic performance requirements are met. This paper provides some prelliminary evaluation of the hydraulic reservoir capacity of a full depth permeable pavement for potential highway application.

### 1.2. Focus of the paper

The focus of this paper is to present the hydralic modeling simulation performances performed under the following factorials:

1. Two pavement scenarios: (a) full depth permeable traveled way pavement, and (b) three-lanes conventional impervious pavement with full depth permeable shoulder.
2. Two permeable gravel reservoir thicknesses at 400 mm and 600 mm.
3. Three climate regions (North, Central, and Southern California).

## 2. METHODS

### 2.1. Modelling approach

The hydraulic flow model used in this paper is based on Richard’s equation that accounts for both saturated and unsaturated conditions. Richards’s equation, fundamentally developed based on Darcy’s law in unsaturated media takes the effect of negative matric potential as well as the dependence of hydraulic conductivity to water content into account. Richards Equation has been widely used for modeling of the flow of water in shallow infiltration into soil, under the assumption that

Darcy's law applies and that the soil properties are approximately uniform in space. Richard's equation for one-dimensional vertical flow can be written as follows):

$$\frac{\partial \theta}{\partial t} = -\frac{\partial K(\theta)}{\partial z} + \frac{\partial}{\partial z} \left[ K(\theta) \left( \frac{\partial \psi}{\partial z} \right) \right] \quad [1]$$

Where:

$z$  = vertical coordinate (the positive direction is assumed to be downward),

$\theta$  = volumetric water content, written as  $\theta(z, t)$  as a function of depth and time,

$K(\theta)$  = hydraulic conductivity, dependent on water content,

$\psi$  = matric potential in the soil defined as the negative of pressure head.

In Eq. [1], the first term in the right hand side is flow due to gravity and the second term is flow due to capillary pressure gradient or capillary diffusivity. We have implicitly assumed that no lateral transport of water occurs outside of the pavement section depicted in Figure 1, by virtue of the one-dimensional nature of the equation. The soil water retention relationships suggested by van Genuchten (1980) and Mualem (1976) were used to determine the variation of hydraulic conductivity and capillary suction as a function of moisture content.

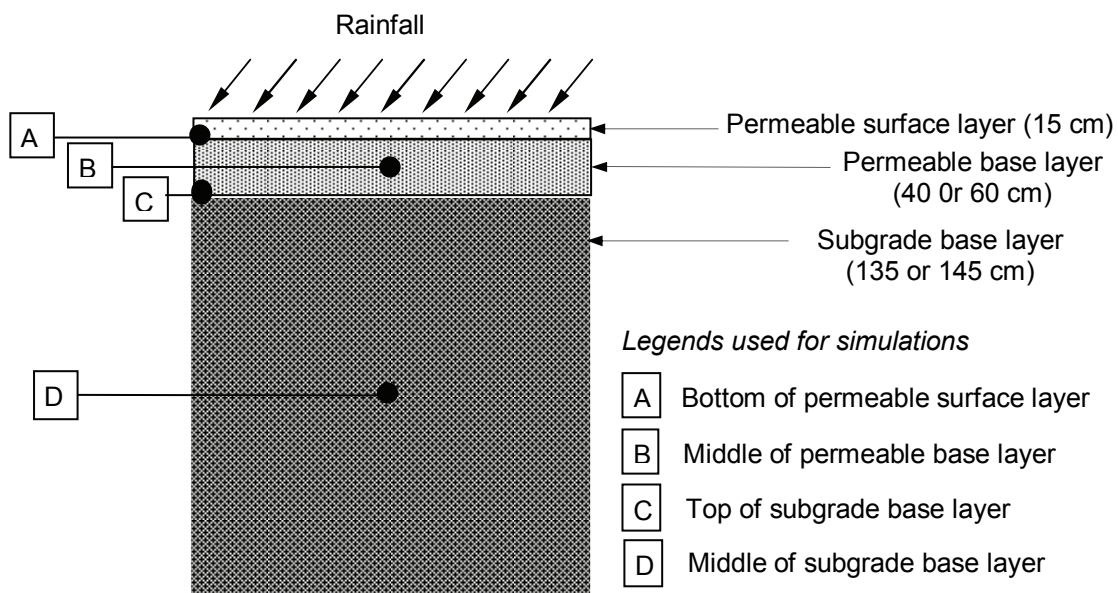


Figure 1. Cross section of different layers for full depth permeable pavement considered in the model

The model was completed by specification of the water boundary conditions, and by the specification of the function  $K(\theta)$  that shows how the hydraulic conductivity depends on water content. This latter function was modeled using Mualem's approach (Mualem, 1976).

$$K(S) = K_s S^{1/2} \left[ 1 - \left( 1 - S^{1/m} \right)^m \right]^2 \quad [2]$$

where  $S$  is the relative moisture content defined as :

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad [3]$$

where  $\theta_s$  and  $\theta_r$  are respectively saturation and residual moisture contents and  $K_s$  is the saturated hydraulic conductivity. Also Van Genuchten Equation is used to establish the relationship between the moisture content and the matric potential.

$$\theta = \frac{\theta_s - \theta_r}{\left[1 + \alpha(-\psi)^n\right]^m} \quad [4]$$

## 2.2. Simulation procedures

To perform the simulation, several assumptions were made. First, the travel time between the location of runoff generation and the location of percolation was ignored. This is a reasonable assumption due to the fact that the time scale for runoff travel is small compared to the infiltration time scale and the model time scale in general. Second, we have assumed that water percolates vertically downward into the ground (i.e. there is no lateral diffusive water flow as well as flow due to horizontal pressure head gradients). This assumption is conservative since allowing water to flow horizontally will provide more room for water retention in the system. Therefore, regardless of the number of highway lanes, a one-dimensional model can be used.

The input parameters used in this modelling effort are shown in Table 1. The permeability values and the retention curve parameters  $n, m$  and  $\alpha$  for each subgrade material was obtained from USDA (1995), in which the soil hydraulic parameters are expressed based on soil texture information. Simulations were performed based on the specific objectives of the study. In particular, three climatic regions were selected to evaluate the performance of the model under three representative rainfall events in California. The rainfall data were obtained from the National Climatic Data Center (NCDC). In order to find the most critical rain record for the design purpose, the year containing the precipitation with the highest volume was chosen. The entire annual precipitation record for the selected year was used to find the number and the total volume of overflow during the critical year and the simulations were performed over the entire year. When performing the optimum permeable base layer, the rainfall data were selected to represent the worse rainfall in the past 30 years of wet season. However, an annual simulations for a wet season was performed to determine the number of overflow based on the optimum permeable base depth obtained under 24 hours design rainfall simulation. For the purpose of these simulations the wet season was defined from October 1 through April 30. In addition, for all simulations, one conservative case of relatively impermeable clay was assumed for subgrade materials. Since the subgrade clay layer was basically impermeable, the simulations were basically carried out to determine the adequacy of permeable granular base layer(s) height under the worst rainfall conditions.

Model Input	Unit	Porous surface material	Open graded aggregate base layer	Subgrade clay layer
Thickness	cm	4.5	400, 600	N/A
Permeability	cm/sec	0.01	0.008	0.00005
Empirical constant, $\alpha$	--	14.5	14.5	9
Empirical constant, $m$	--	0.5	0.5	0.5
Empirical constant, $n$	--	2	2	2

Note: For input parameters  $\alpha, m$  and  $n$  refer to Equations [2] to [4].

Table 1. Inputs parameters used in hydraulic modeling simulations

## 3. RESULTS AND DISCUSSION

### 3.3. Simulations performance

The simulation performance results were presented based on the saturation content as well as flow in each layer that is produced from the representative rainfalls. Under each rainfall, the permeable granular subgrade height was adjusted in order to determine if the assumed height is sufficient or not. For this simulations, it is important to note that we assumed the subgrade soil was totally impermeable and hence all rainfall volume was captured within the permeable granular subgrade layer.

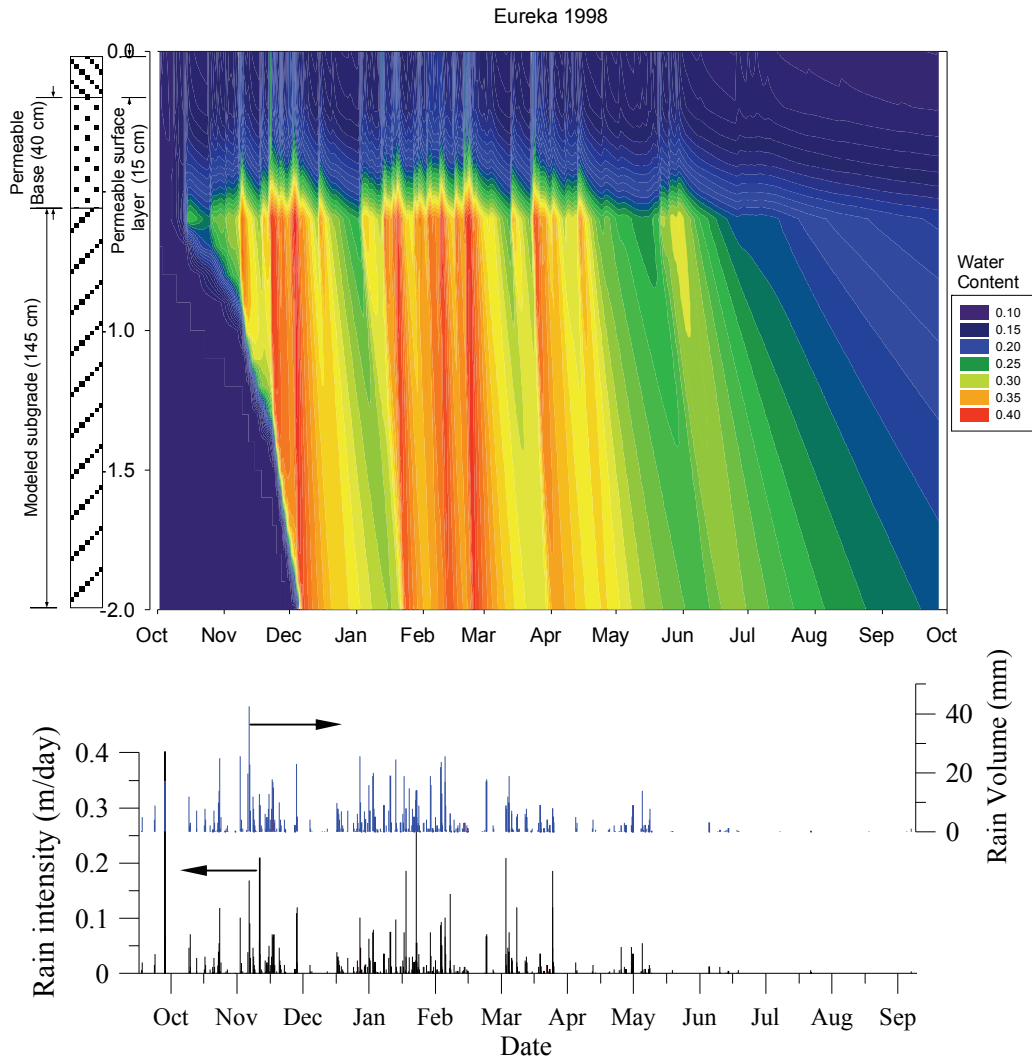


Figure 2. Contour map of saturation water content for northern California (Eureka) with permeable gravel reservoir base thickness of 400mm (16 in.)

## Los Angeles 1998

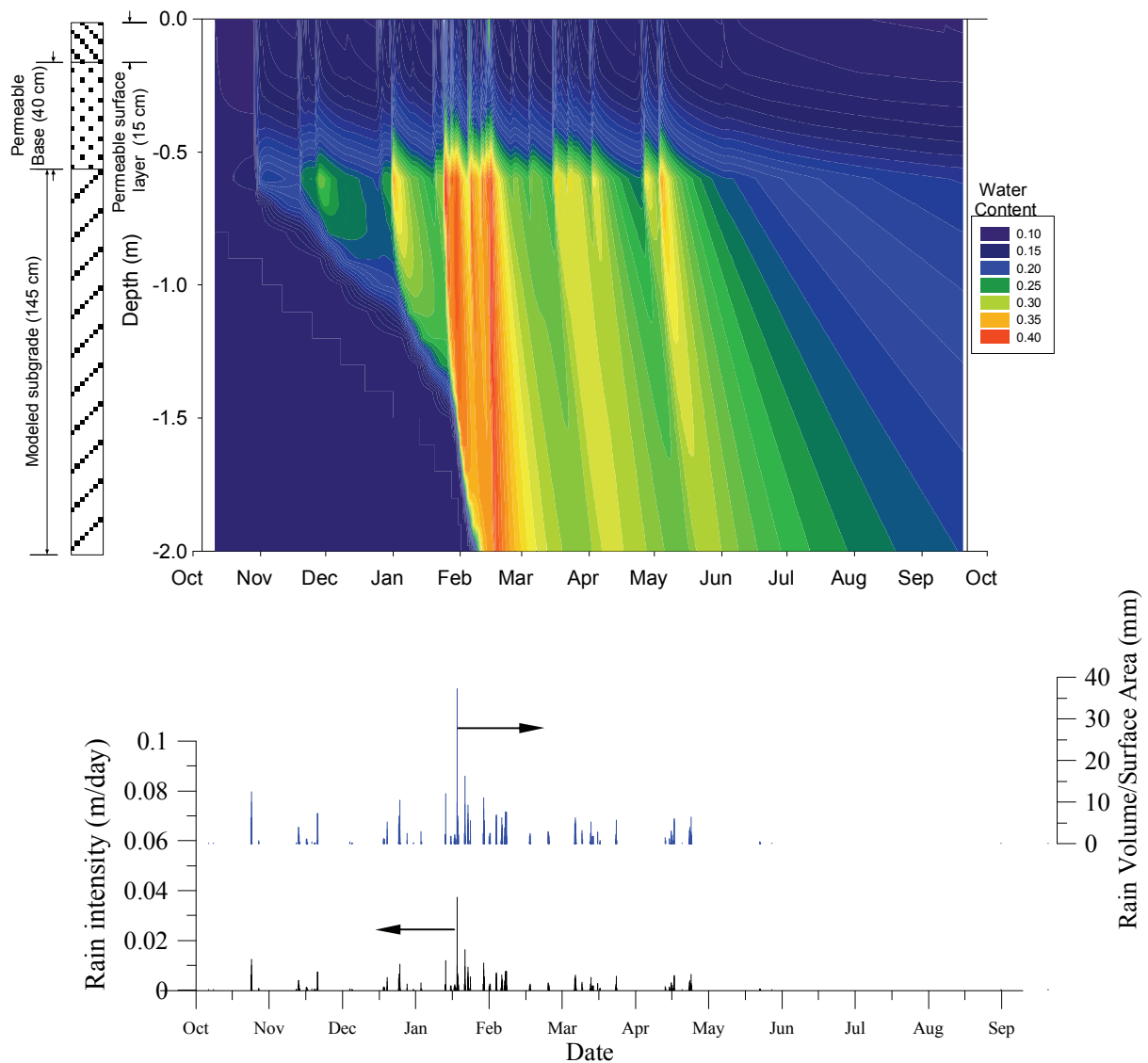


Figure 3. Contour map of saturation water content for southern California (Los Angeles) with permeable gravel reservoir base thickness of 400mm (16 in.)

The results of these analyses are summarized in Table 2. Selective simulation results for three climate regions with a traveled way permeable subgrade thickness of 400 mm are shown in Figures 2 through 4. In addition, the simulation results for southern California (Los Angeles area) under conventional impervious 3-lanes highway with permeable shoulder thickness of 400 mm is shown in Figure 5. In addition, the water contents and extra voids available to handle extra water contents at various depth of pavement sub-sections were presented in separate plots and evaluated visually. Figure 6 shows the void space left in the system to accommodate possible extra water at different times during the simulation. This curves provides an insight into the risk of overflow when larger storm occur.

Based on the results summarized in Table 2 and contor plots shown in Figures 1-3, a permeable granular base height of 400 mm ( $\approx 16$  in.) for travelled way structure is not adequate to provide sufficient reservoir capacity to hold the water and overflow will occur for worst storm events from all three climate regions. However, a permeable granular base height of 600 mm ( $\approx 16$  in.) under the same storm event condition is sufficient and prevent overflow. For the cases with

Scenario	Reservoir base layer thickness	Subgrade type	Overflow?
Full depth permeable traveled way structure	400 mm (≈16 in.)	clay	Yes
	600 mm (≈24 in.)	clay	No
3-lane impervious with permeable shoulder	400 mm (≈16 in.)	clay	Yes
	600 mm (≈24 in.)	clay	Yes

Table 2. Summary of 1-D hydraulic modeling performance under worst case scenario for three climate regions

three impermeable lanes draining to a permeable shoulder, the model showed that the reservoir base layer of 600 mm (≈24 in.) was not sufficient. One representative contour map for impervious runoff drained into permeable shoulder for Los Angeles area is shown in Figure 4. In general, the simulation results revealed that where only the shoulder is permeable, a greater thickness of granular material is needed. Major reason for this is that the shoulder has much less surface area for infiltration compared to when the subgrade under the entire pavement is accessible for infiltration. Alternatively, whenever possible, the shoulder width can be extended to provide additional reservoir capacity within the permeable granular layer.

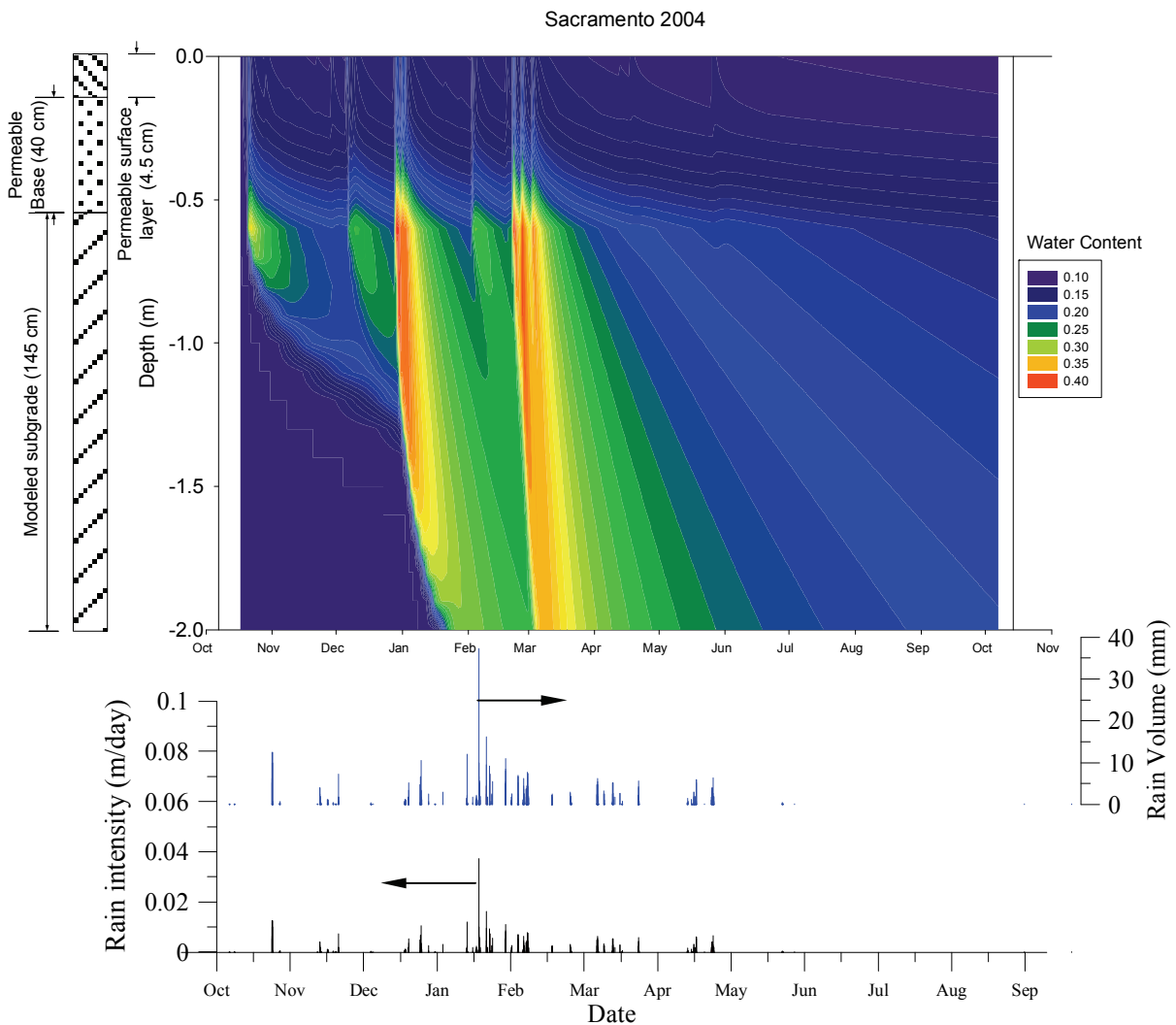


Figure 4. Contour map of saturation water content for central California (Sacramento) with permeable gravel reservoir base thickness of 400mm (16 in.)

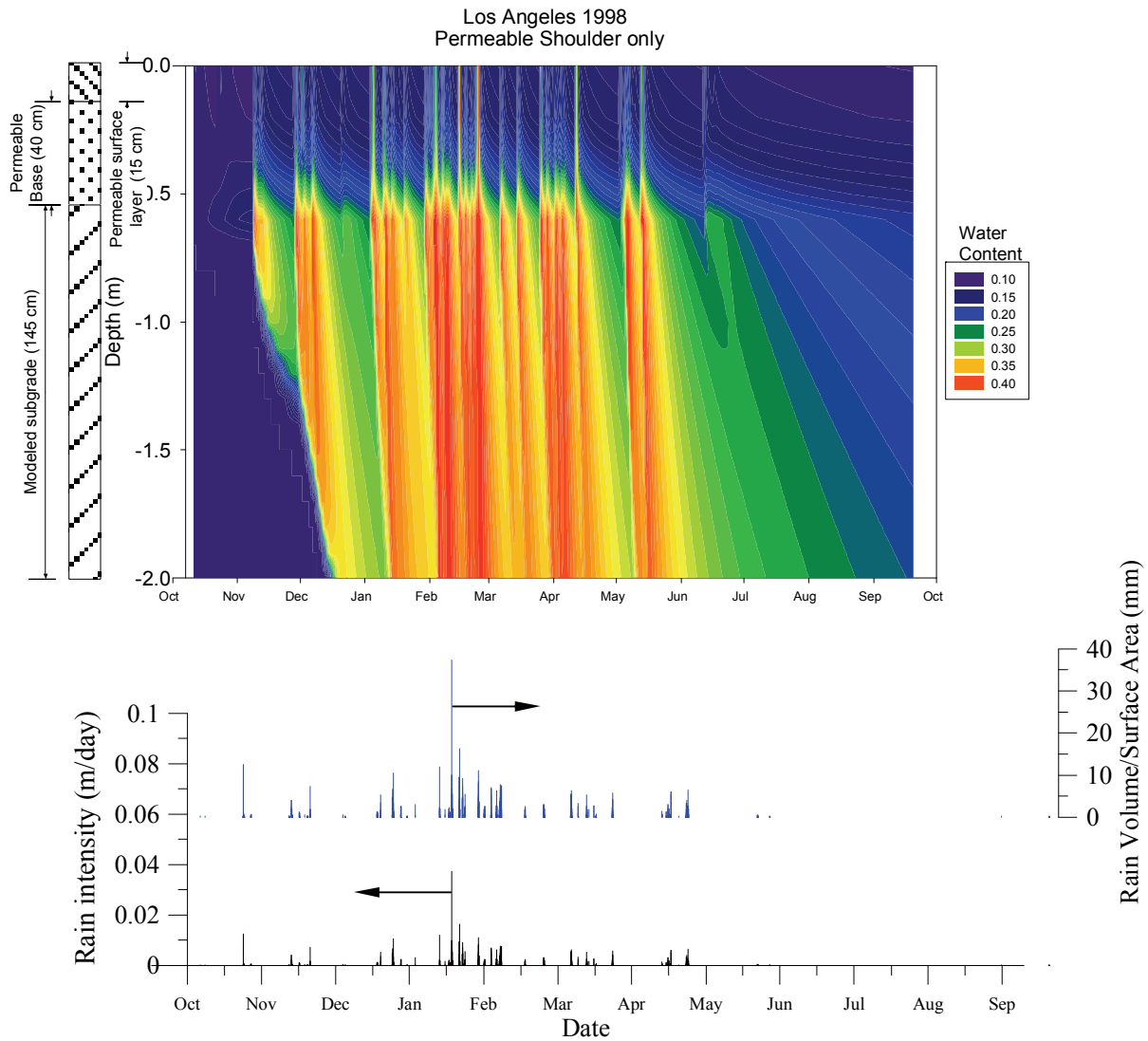


Figure 5. Contour map of saturation water content for southern California (Los Angeles) with impermeable 3-lane driveway and full depth permeable shoulder (16 in.)

If the permeable pavements are not maintained properly, the particles that accumulate on the pavement surface may clog the pores thereby inhibiting the passage of water through the surface of the pavement. This diminished permeability may increase the runoff quantity and will reduce any of the water quality improvements provided by the infiltration process. For this reason, when permeable pavement is used in freeways some type of cleaning technology must be employed to ensure infiltration. The clogging issue and maintenance is beyond the scope of this study and need to be investigated separately.



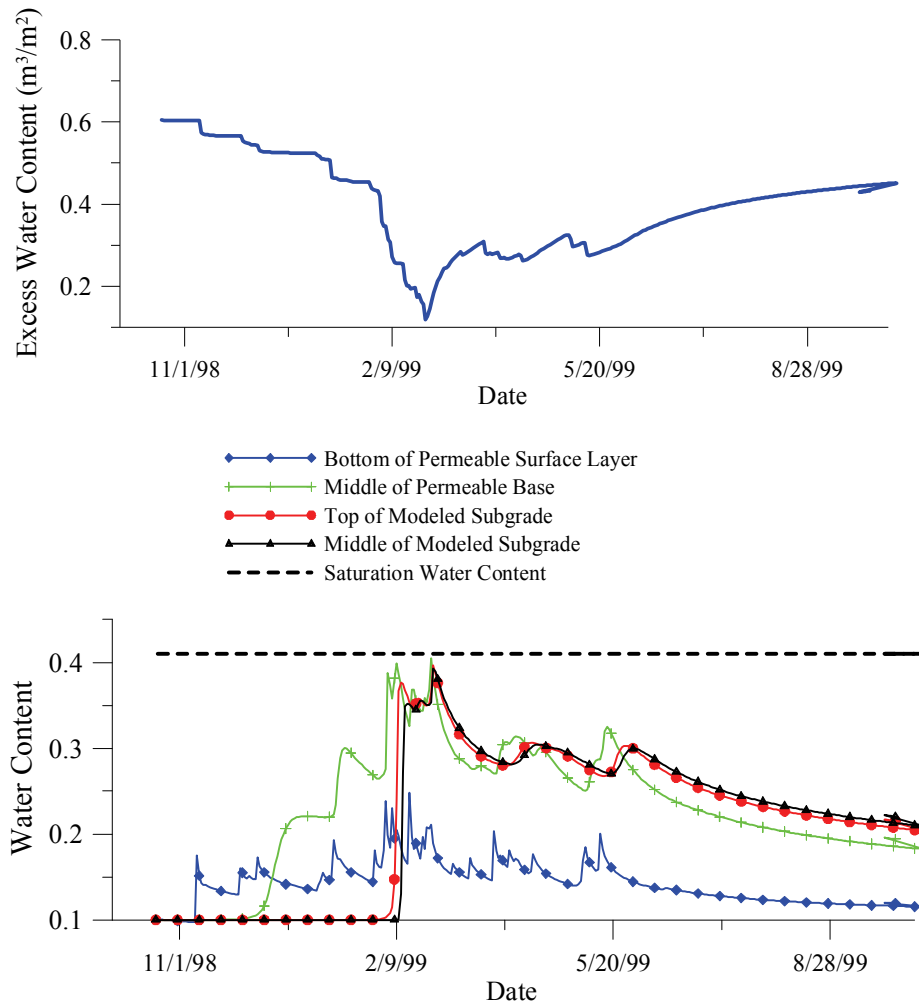


Figure 6. Water content and extra water holding capacity available at various locations within the pavement structure for Los Angeles area. (For locations of the simulated water content refer to Figure 1).

#### 4. CONCLUSIONS

The conclusion drawn from this one dimensional hydraulic analyses of full depth permeable pavement structures are as follows:

- The required thickness of the permeable granular base layer is about 600 mm or less depending upon the subgrade soil permeability and storm event. This preliminary thickness estimation is conservative since the sub-base soil was assumed to be highly compacted clay with minimum permeability. Smaller permeable granular layer may be needed when the sub-base soil is not clay or less compacted.
- This simulation result indicate that where only the shoulder is permeable, 600mm thickness of granular material is not sufficient and a higher thickness or wider shoulder is needed to capture all stormwater runoff without excess water.

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