# AN ADVANCEMENT IN HYDRAULIC MODELING OF POROUS PAVEMENT FACILITIES

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## ACKNOWLEDGEMENTS

The study addressed in this paper was part of a comprehensive investigation of operational characteristics of porous and conventional paving systems conducted by Espey, Huston & Associates, Inc. and the City of Austin, Texas. The project was executed in fulfillment of Grant No. R806338-01-2 with the City of Austin, under the sponsorship of the U.S. Environmental Protection Agency. A report documenting the entire project will be completed during the summer of 1983.

## INTRODUCTION

The liabilities of urban development to indigenous water resources are generally accepted to be manifested in stormwater runoff peaks and event volumes of greater magnitude than in the predeveloped state, often occurring in association with a degradation of receiving water quality. The increase in impervious areas such as roofs, streets, and parking lots in urban areas reduces the infiltration capacity of urban watersheds and produces a corresponding increase in runoff rates and volumes. Stormwater runoff from developed areas has been recognized as a source of contaminant loading to surface and ground water bodies. Impervious areas generally have limited assimilative properties and in some cases tend to yield contaminants that are not amenable to control and removal using standard treatment procedures(1). Stormwater flows transport contaminants which have accumulated on the watershed during dry weather, however, the total mass transported is a function of the contaminant accumulation rate, the number of antecedent dry days, the intensity of the rainfall, the velocity and volume of surface flow and other physical properties of the catchment. Heavy metals, exhaust products, oils and other hydrocarbons from automobiles and machinery, suspended solids from dust and dirt accumulation and airborne pollutants washed out during precipitation events are typical contaminants present in urban stormwater runoff(4).

Stormwater management generally consists of collecting and transporting overland runoff in a conveyance system of storm sewers and possibly channels which are tributary to a nearby stream or lake. Although local flooding problems may be solved by this system, the shorter time of concentration and higher peak flows which are generated may tend to create more severe flood problems downstream. The increase in flow velocities in the improved channels creates a high erosion and scour potential, thus exacerbating the problem of pollutant transport to receiving bodies of water.

## POROUS PAVEMENTS

A porous pavement facility is an innovative solution to the problem of stormwater drainage from parking and other low density traffic areas in the urban landscape. This type of pavement uses the natural infiltration capacity of the soil to absorb rainfall and local runoff after accumulation in a porous base, consisting of sand or large diameter open graded gravel. If infiltration into the soil is undesirable or not practical, lateral drainage to a sump or channel may be provided. Porous pavement systems can be designed to minimize changes in the runoff quantity and quality characteristics of a watershed during and after development. A cross-section of a typical porous pavement facility is presented in Fig. 1.

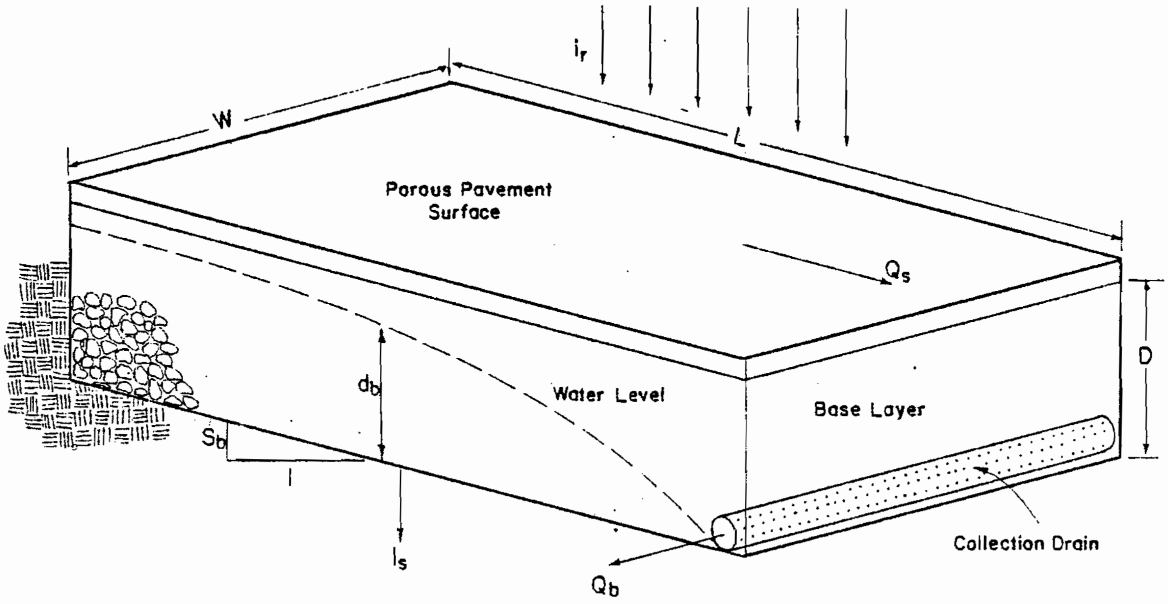
In regular applications for highway and airport runway construction, a commonly used porous pavement surface has been referred to as plant mix seal coat, open graded mix, gap graded mix, popcorn mix, or porous friction course(2). This material consists of an open graded asphalt and concrete mixture with a high percentage by weight of aggregate larger than a number four seive, laid to a thickness of ½ to 1 inch. The resultant paving has a coarse surface texture and a high void ratio resulting in temporary storage of surface water while maintaining the coefficient of friction between a vehicle tire and pavement at values comparable to the coefficient under dry conditions. The open graded asphalt mixture underlain by a gravel base course with appreciable storage capacity is the most frequently used type of porous pavement. The whole system may be isolated from the natural ground by an impermeable membrane such as a polyethylene liner, in which case some type of artificial drainage would be needed; or, the porous pavement system may be allowed to drain into the natural ground at all points of contact. The latter arrangement does not preclude the use of artificial drains, as in the case of highly impervious natural ground. Where storage is provided, flow control devices can be incorporated to regulate the release rate, e.g., to prevent discharge during a predetermined period after a storm event.

By design, several inches of rainfall and runoff can be stored within a porous pavement system prior to discharge. The pavement can be designed to retain all of the runoff with no drainage from the site, to retain a sufficient volume of runoff to reduce the after-development hydrologic conditions to predevelopment conditions, or to delay runoff from the site, thus attenuating peak discharges and reducing the impact of associated pollutant transport. Any combination of these properties can be incorporated into an overall project drainage design to satisfy municipal or watershed drainage management criteria.

Pollutant removal mechanisms in a porous pavement system have not been fully documented. The relatively slow hydrodynamics may allow some settling of suspended matter. Adsorption to and absorption in the base media may also be realized. Although transport of soluble constituents into the ground via infiltration removes them from the porous pavement system, subsequent groundwater transport to receiving waters may result.

## SIMULATION OF STORMWATER HYDRAULICS

Prediction of hydraulic characteristics is a valuable tool for assessing the performance of stormwater runoff control strategies. Stormwater hydraulic



| | |
|---|---|
| L | length of pavement |
| W | width of pavement |
| D | depth of base layer |
| $S_b$ | slope of base layer |
| $i_r$ | rainfall intensity |
| $i_s$ | infiltration rate |
| $d_b$ | depth of water in base layer |
| $Q_s$ | surface discharge |
| $Q_b$ | collection drain discharge |

Fig. 1. CROSS SECTION OF TYPICAL POROUS PAVEMENT FACILITY

characteristics of porous and nonporous pavement study sites were evaluated using a revised version of the computer model PORPAV, initially developed for incorporation into the EPA Storm Water Management Model (SWMM)(3). PORPAV is a two-dimensional dynamic water budget analysis of a pavement facility. The utilization of PORPAV allows a comprehensive analysis of flow and storage in porous and nonporous pavement facilities, facilitating comparisons of the hydraulic response of alternative pavement designs. The computational scheme of PORPAV is described below.

The rate of inflow to the pavement facility from rainfall and, if present, any contributing area is compared to the permeability of the porous pavement for each time interval. For porous systems in general, the permeability is much greater than the inflow rate and all of the water moves into the pavement control volume. For nonporous pavements the permeability is generally less than the inflow rate and limited portion of the inflow moves into the pavement. The excess is stored on the surface of the pavement for subsequent computation of surface runoff from the facility.

The inflow into the pavement control volume is added to the existing storage and then compared to the permeability of the base. If the base permeability is greater than the stored volume in the pavement, all of the flow is transferred into the base control volume. This is true for most porous pavement systems operating according to design. In those instances where the base permeability is less than the inflow volume, the inflow into the base is computed as the vertical seepage into the base, at a rate limited by the smaller of the pavement or base permeabilities. The lateral outflow from the pavement top layer volume is assumed to be negligible as compared to the vertical flux. The difference between the flow into the pavement and the transport to the base layer is stored in the pavement control volume.

The inflow to the base control volume is added to the existing base volume. The revised PORPAV includes a routing procedure to account for the vertical transport of water within the layers, simulating the vertical movement of the wetting front as it passes through the pavement system. In essence, volumes of water, defined by the permeability of the layer and the length of the computational time step, are routed through the depth of the layer. PORPAV allows the option of utilizing single or multiple collection drains for discharge from the base layer. An expression for estimating the horizontal discharge from the porous pavement base was developed to reflect the nonsteady flow regime in the porous media. Darcy's Law was employed as the governing flow equation(5),

$$Q_b = K_b A \, dh/dx$$

where $Q_b$ is the average horizontal discharge;
$K_b$ is the permeability of the base media;
A is the cross-sectional area of flow; and,
$dh/dx$ is the energy gradient.

The energy gradient was approximated by

$$dh/dx = H/L$$

where H is the total elevation potential, equal to $d_b + LS_b$;
$d_b$ is the depth of water in the base layer;

L is the normal length of the base layer; and,
$S_b$ is the slope of the base layer.

The cross-sectional area of flow was approximated as

$$A = wd/2$$

where w is the width of the layer.

This yields

$$Q_b = (K_b w S_b)\, d_b/2 + (K_b w)\, d_b^2/2L$$

or on a unit area basis,

$$q_b = c_1 d_b + c_2 d_b^{\ 2}$$

where $c_1 = K_b S_b/2L$; and,

$c_2 = K_b/(2\cancel{S}\cancel{S}L^2)$.

When there is no impermeable seal present to restrict flow, some horizontal discharge will occur to the adjacent soil. However, this horizontal flux is generally negligible when compared to the vertical component leaving the layer via infiltration because of the much smaller cross-sectional area of flow. Also, the moisture content of the surrounding soil increases during the storm event, thereby reducing the hydraulic energy gradient between the porous media and the soil. In a narrow, high-wall trench without an impermeable seal or a drain pipe, the horizontal flux to the soil during the initial period of the storm, before the hydraulic gradient between the base and the soil diminishes, may be of the same order of magnitude as the infiltration flux. By neglecting the horizontal flux when there is no impervious seal present this assumption represents a conservative case with regard to the effective storage of the porous pavement system.

PORPAV incorporates Horton's equation to describe the variable rate of infiltration during and subsequent to a precipitation event. This was expressed as

$$i_s = i_f + (i_o - i_f)\, e^{-kt}$$

where $i_s$ is the infiltration rate at time t;
$i_f$ is the infiltration capacity (minimum rate) of the soil;
$i_o$ is the initial infiltration rate;
k is the first-order decay coefficient; and,
t is the elapsed time.

The initial infiltration rate is dependent on the initial moisture condition of the soil. The difference between the initial and minimum infiltration rates can result in significantly greater vertical transport calculated during the storm event. If a constant infiltration rate is preferred, the initial rate may be replaced by the infiltration capacity (minimum rate) of the soil. If the bottom is sealed with an impermeable membrane, no flow is discharged to the natural ground. The difference between the inflow to the base layer and the outflows (vertical and lateral) from the base is stored in the base control volume.

All stored volumes within each layer are compared to maximum void volumes. If the storage volume in the base is exceeded, the excess is stored in the pavement; if the storage volume in the pavement is exceeded, the excess is addded to the surface storage on the pavement, if any exists. Surface runoff is then computed as broad channel flow from the pavement using Manning's equation.

Provisions were added to PORPAV to calculate the theoretical detention time provided by a pavement facility. This duration was calculated as the elapsed time between the center of mass of the inflow hydrograph and the center of mass of the discharge hydrograph. Additionally, average and cumulative inflow, peak and cumulative discharge and other discharge hydrograph characteristics are compiled for each simulation.

## DESCRIPTION OF THE MONITORING SURVEYS

An extensive monitoring program was initiated to document hydraulic characteristics of several pavement systems. A monitoring network of three parking lots was selected, representing a variety of pavement surfaces. The following text discusses the physical characteristics and sampling procedures for each of the study lots.

### Porous Asphalt Lot

A plan drawing of the porous asphalt study lot is presented in Fig. 2. The porous asphalt lot consisted of three layers of stone and asphalt constructed on an impervious limestone bedrock base. The lowest layer was made up of a stone base course with rocks ranging from 1.5 to 2.5 in (3.0-6.5 cm) in diameter. This base ranged in depth from approximately 4 in (10 cm) on the upslope end to 42 in (107 cm) on the low end and provided a void space of approximately 40 percent of its volume for water retention. The second layer averaged 2 in (5 cm) in depth and consisted of a stone top course (filter course) with material ranging from 0.4 to 0.6 in (1.0-1.5 cm) in diameter. This intermediate layer was selected to provide a uniform surface for the application of the porous asphalt. The final layer consisted of 2.5-in (6.4 cm) of porous asphalt mix with 5.5 to 6.0 percent asphalt content.

The original design called for runoff to be monitored within a collection basin located at the downslope corner of the lot. A 6-mil polyethylene impermeable liner was installed along the above-grade downslope width and side to prevent seepage. However, this seal leaked and the base discharge did not flow into the monitoring barrel. Small trenches and berms were constructed along the periphery of the lot to ensure all runoff was captured. However, these trenches were not lined and, consequently, some percolation and erosion inevitably occurred. A 90-degree V-notch weir was installed below the lot in order to measure the discharge rates. Visual stage readings at this weir by the field crew were used as a basis for the runoff calculations.

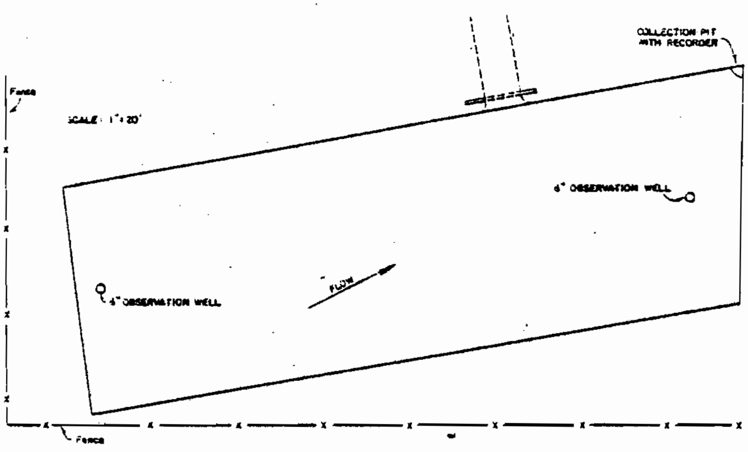


Fig. 2.

KRAMER LANE MAINTENANCE YARD

POROUS ASPHALT

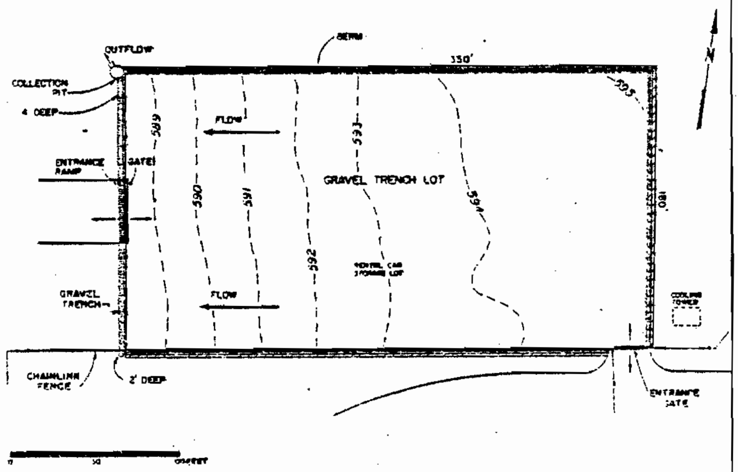


Fig. 3.

AUSTIN MUNICIPAL AIRPORT

GRAVEL TRENCH LOT

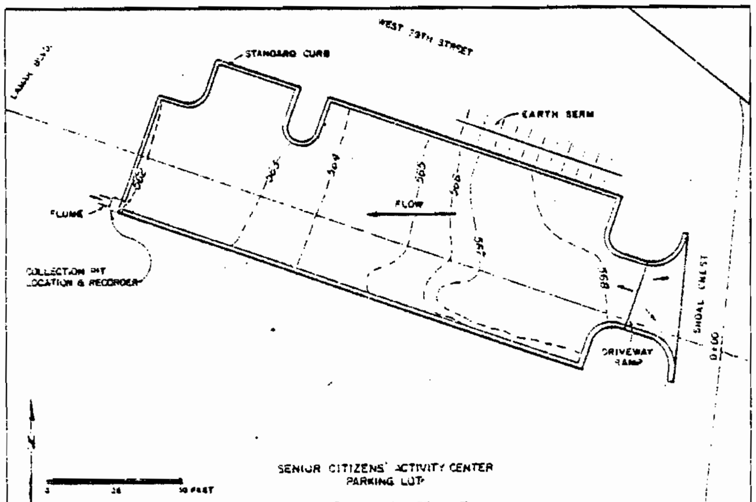


Fig. 4.

SENIOR CITIZENS' ACTIVITY CENTER
PARKING LOT

CONVENTIONAL ASPHALT

### Gravel Trench Lot

A plan drawing of the gravel trench lot is presented in Fig. 3. The study area consisted of a conventional asphalt lot with a 4-ft (1.2-m) wide and 3-ft (0.9-m) deep drainage trench at the downslope end. The trench was lined with a 6-mil polyethylene impermeable membrane and filled with 1.5 to 2.5 in (3.8-6.4 cm) diameter crushed stone, cleaned and washed. This base was topped with approximately 1 ft (30 cm) of smaller than 1-inch (2.5-cm) diameter gravel. The trench was subsequently flushed with several volumes of water to rinse out construction fines. Stormwater flows within the drainage trench were monitored within a 55-gallon (208-l) barrel. A 4-in (10-cm) diameter pipe was used as the discharge control. All discharges were calculated based on readings of the water level within the barrel by the field crew.

### Conventional Asphalt Lot

A plan drawing of the conventional asphalt lot monitored in the Austin study is presented in Fig. 4. Runoff discharge estimates were estimated from water levels in a 3 x 3 x 1.5 ft (0.9 x 0.9 x 0.5 m) 90-degree V-notch box weir.

## SPRINKLER-GENERATED RUNOFF EVENTS

Sprinkler-induced "storms" provided the ability to control the intensity, duration and timing of the inflows at the study sites. Impact-type sprinklers, supplied by the City of Austin Parks and Recreation Department, were used during the tests with the City's fire hydrants used as the source of water. Field observations indicated a spectrum of spray droplet sizes, ranging from fine mist at the periphery of the spray stream to large droplets in the center. A similar range of drop sizes were observed during natural storm events. The number of sprinkler heads were varied for each induced storm and care was taken in placement of the heads to provide uniform coverage of the lot. A schematic of the sprinkler application is presented in Fig. 5. Equivalent rainfall estimates were obtained by placing eight wedge type rain gages on wooden stands around the test lot. During the tests, readings of the rain gages were made at regular intervals (every 15 to 30 minutes) and at the conclusion of the event. Once the individual rainfall totals were compiled, the values were averaged to provide an approximation of the total event volume.

The gravel trench lot was too large for sprinkler coverage, so 2000-gallon (7600-l) capacity rear-end-dispensing water trucks provided by the City of Austin were used. The trucks drove slowly across the upper end of the lot releasing water at approximately 300 gallons per minute (19 l/s). Different event intensities were obtained by varying the number of trucks used, trips made, and number of trucks releasing at one time.

## RESULTS OF THE MONITORING SURVEYS

Hydraulic performance results obtained in the stormwater surveys are discussed below. A summary of hydraulic characteristics of the pavements during each runoff event is presented in Table 1.

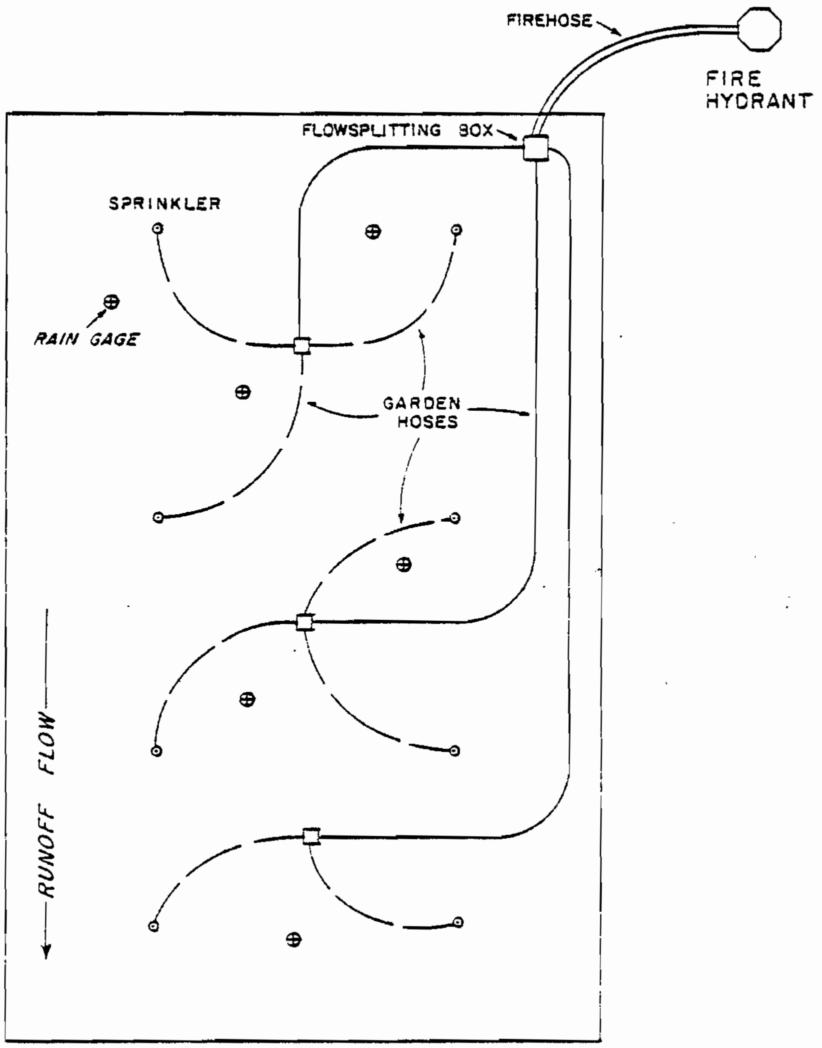


Fig.5. Schematic of Sprinkler Application

## TABLE 1

## HYDRAULIC SUMMARY OF STORMWATER SURVEYS

| Pavement Type | Event Date | No. of Sprinklers[1] | Total Inflow (in) | Duration (min) | Average Intensity (in/hr) | Peak Discharge (cfs) | Time to Peak (min) | Total Discharge (in) | Runoff Ratio[2] (in/in) | Antecedent Rainfall[3] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | 7-Day (in) | 14-Day (in) |
| Porous Asphalt[4] | 03/22/82 | 8 | 0.94 | 60 | 0.94 | 0.269 | 58 | 0.58 | 0.73 | 0.02 | 0.03 |
| | 06/01/82 | 8 | 1.53 | 55 | 1.67 | 0.237 | 53 | 0.56 | 0.37 | 0.00 | 0.00 |
| Gravel Trench | 03/03/82 | 3 | 0.64 | 94 | 0.41 | 0.440 | 60 | 0.49 | 0.76 | 4.03 | 4.03 |
| | 03/19/82 | 4 | 0.64 | 70 | 0.56 | 0.580 | 66 | 0.41 | 0.64 | 0.03 | 0.03 |
| | 04/04/82 | 4 | 0.64 | 60 | 0.65 | 1.667 | 55 | 0.49 | 0.77 | 0.12 | 1.31 |
| Asphalt | 06/03/81 | * | 0.34 | 46 | 0.44 | 0.84 | 53 | 0.40 | 1.18 | 2.48 | 7.26 |
| | 05/11/82 | 8 | 0.21 | 10 | 1.26 | 0.22 | 7 | 0.15 | 0.71 | 0.99 | 1.03 |

1 in = 2.54 cm
1 cfs = 28.31 l/s
1 in/hr = 2.54 cm/hr

[1] Values for the gravel trench are the number of water trucks used.

[2] Runoff-to-rainfall ratio.

[3] Precipitation amounts recorded at the Austin Airport within the indicated number of preceding days.

[4] Discharge results influenced by infiltration lines along trenches.

*Denotes natural precipitation event. The remainder were sprinkler-induced events.

# TABLE 2

## INPUT DATA FOR PORPAV SIMULATIONS

| Element | Parameter | Unit |
|---|---|---|
| Rainfall rate | Magnitude | in/hr |
| Pavement surface | Length | ft |
| | Width | ft |
| | Slope | ft/ft |
| | Area | $ft^2$ |
| | Permeability | in/hr |
| | Depth | in |
| | Porosity | $ft^3/ft^3$ |
| | Initial dead storage | in |
| | Manning's n coefficient of roughness | $ft^{1/6}/s$ |
| Pavement base | Permeability | in/hr |
| | Depth | in |
| | Porosity | $ft^3/ft^3$ |
| | Initial and dead storage | in |
| | Collection drain capacity | in/hr |
| Natural soil | Initial and final infiltration rate | in/hr |
| | Horton's infiltration decay coefficient | $hr^{-1}$ |

### Porous Asphalt Lot

A maximum intensity of 1.67 in/hr (3.5 cm/hr) was achieved with no resulting surface runoff at the porous asphalt lot. As presented in Table 1, the total discharge volume, the time to peak flow and the peak discharge rates were similar for each event although the inflow varied from 0.94 in (2.4 cm) to 1.53 in (3.8 cm) and the nominal intensity varied from 0.94 in/hr (2.4 cm/hr) to 1.67 in/hr (4.2 cm/hr). Observed base runoff ranged from 37 to 73 percent of recorded sprinkler inflow. Runoff ratios less than unity were attributed to wetting of the base media, storage within the base layer and percolation along the trenches.

### Gravel Trench Lot

Table 1 includes a summary of the sprinkler events monitored at the gravel trench lot. The application rates were not varied enough to produce significantly different discharge characteristics. Observed runoff ranged from 64 to 77 percent of recorded inflow, with an average of 72 percent for the three events. Observations made during storm events indicated the small diameter surface gravel was impeding the vertical flux of water, i.e., runoff was flowing across the top of the trench.

### Conventional Asphalt Lot

A sprinkler-generated runoff event and a natural precipitation event were monitored at the conventional asphalt study lot, and the results are summarized in Table 1. Estimated runoff volumes ranged from 71 to 118 percent of recorded rainfall. The runoff ratio greater than unity was attributed to rainfall measurement error.

## STORMWATER SIMULATION RESULTS

Stormwater hydraulics for each pavement type were simulated with PORPAV. PORPAV was calibrated for each lot using the initial set of observed runoff data. The remaining events were subsequently simulated as verification. A list of PORPAV input data is presented in Table 2. Pavement characteristics such as pavement length, width and depth were obtained from onsite or construction measurements. Other parameters such as the Manning's roughness coefficient, volume of dead storage on the pavement and pavement porosity were estimated. Records of observed inflow were input to PORPAV. Calibration of the model was initialized by varying values of the estimated parameters to reproduce the observed runoff volume. Generally this was accomplished by adjusting the base void volume (the product of depth and porosity) for the pervious lots and the volume of surface storage for the impervious lots. The second objective was to reproduce the observed peak runoff rate. Variations in runoff rates were effected by varying the estimates of average surface slope and the roughness coefficient. For the porous asphalt and gravel trench lot the coefficient of permeability for the base layer was varied to reproduce the observed peak base discharge rate. Results of the simulations are discussed below. A comparison of simulated and observed hydraulic characteristics is summarized in Table 3.

## TABLE 3

## SIMULATION RESULTS
## POROUS ASPHALT LOT

| | Peak Flow (cfs) | Time to Peak (min) | Runoff Volume (cubic feet) | Detention Time (min) |
|---|---|---|---|---|
| POROUS ASPHALT LOT - STORM 1 | | | | |
| Observed | 0.27 | 58 | 745 | 42 |
| Simulated | 0.273 | 50 | 745 | 28 |
| Deviation | +0.003 | -8 | 0 | -14 |
| POROUS ASPHALT LOT - STORM 2 | | | | |
| Observed | 0.24 | 53 | 721 | 42 |
| Simulated | 0.514 | 55 | 1,409 | 25 |
| Deviation | +0.274 | +2 | +688 | -17 |
| GRAVEL TRENCH LOT - STORM 1 | | | | |
| Observed | 0.44 | 60 | 1,960 | 29 |
| Simulated | 0.497 | 90 | 2,107 | 24 |
| Deviation | +0.057 | +30 | +147 | -5 |
| GRAVEL TRENCH LOT - STORM 2 | | | | |
| Observed | 0.58 | 66 | 1,693 | 24 |
| Simulated | 0.487 | 70 | 1,650 | 24 |
| Deviation | -0.093 | +4 | -43 | 0 |
| GRAVEL TRENCH LOT - STORM 3 | | | | |
| Observed | 1.67 | 55 | 1861 | 19 |
| Simulated | 0.472 | 60 | 1,448 | 23 |
| Deviation | -1.198 | +5 | -413 | +4 |
| CONVENTIONAL ASPHALT LOT - STORM 1 | | | | |
| Observed | 0.84 | 53 | 368 | 1 |
| Simulated | 0.297 | 50 | 269 | 5 |
| Deviation | -0.543 | -3 | -99 | +4 |
| CONVENTIONAL ASPHALT LOT - STORM 2 | | | | |
| Observed | 0.22 | 7 | 138 | 5 |
| Simulated | 0.257 | 10 | 140 | 8 |
| Deviation | +0.037 | +3 | +2 | +3 |

1 cfs = 28.32 lps

1 ft$^3$ = 28.32 l

## Porous Asphalt Lot

The discharge hydrograph for the calibrated data set, presented in Fig. 6a, accurately resembles the observed one, but is advanced about fifteen minutes, as is reflected in the difference in detention times. The calibrated coefficients of dead storage and base permeability were held constant during the simulation of the remaining event. Observed and simulated discharge hydrographs for the final event are displayed in Fig. 6b. The significant overestimation of peak discharge rate and volume probably resulted from an incorrect sprinkler inflow measurement (used as input to PORPAV) or an inconsistent hydraulic response, possibly increased base storage or percolation.

## Gravel Trench Lot

Three artificial rainfall events were simulated for the gravel trench lot. For each case the runoff from the conventional asphalt lot was simulated with PORPAV and subsequently used as input to the gravel trench simulation, hence, characteristics for both facilities had to be determined. A summary of simulation results is presented in Table 3. Coefficients of base permeability and dead storage on the asphalt lot and in the gravel trench were determined by calibrating PORPAV with the initial runoff event data. The calibration hydrograph is presented in Fig. 7a. Runoff characteristics were reproduced quite well for the second event, as displayed in Fig. 7b. Incorporating the same physical characteristics of the asphalt and gravel trench for the final event simulation yielded a less satisfactory comparison, presented in Fig. 7c. The major discrepencies in the two hydrographs of the third event occur during the periods of water release from the water trucks, possibly an artifact of utilizing a constant inflow rate during this period in the simulation.

## Asphalt Lot

Simulation results for the conventional asphalt lot are compared with recorded values in Table 3. The second event was used to calibrate PORPAV and was accurately simulated, as shown in Fig. 8a. The simulated hydrograph for the second event is compared to observed results in Fig. 8b. The simulation did not reproduce the peak discharge rate, possibly a result of a short, intense burst of rain which was undetected in the rainfall data. Both simulations depicted the very rapid detention times associated with the asphalt lot events.

## CONCLUSIONS

The revised PORPAV satisfactorily simulated sprinkler-generated stormwater hydraulics of both porous and nonporous pavement facilities. Sprinkler application rates ranged from 0.4 to 1.7 inches per hour. The favorable simulation results obtained in this study suggest that PORPAV can be used to assess the relative hydraulic performance of pavement facilities available for urban runoff control. The option of using a drain pipe for the base layer discharge has not been evaluated. A future study should be conducted at an existing pavement facility utilizing a collection drain system to assess the ability of PORPAV to simulate such a control strategy.

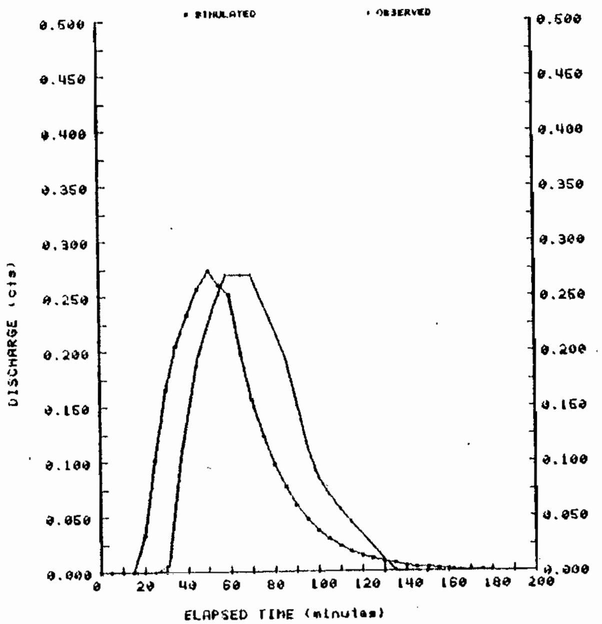


FIG. 6a SIMULATED VS. OBSERVED HYDROGRAPHS FOR 3/22/82.

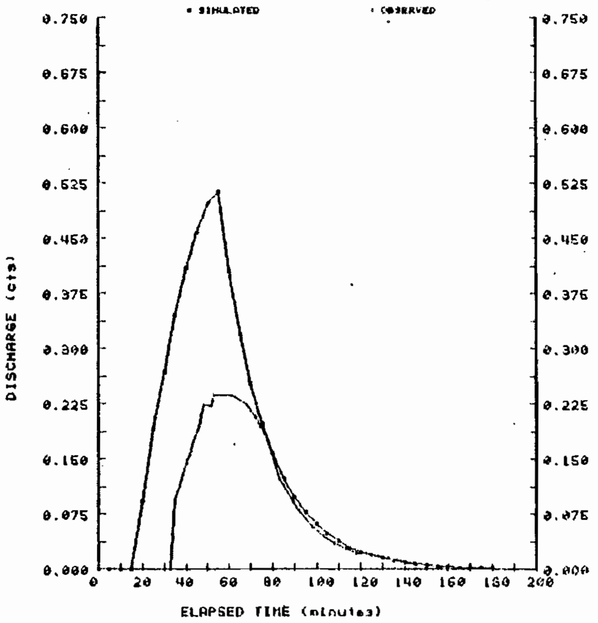


FIG. 6b SIMULATED VS. OBSERVED HYDROGRAPHS FOR 6/1/82.

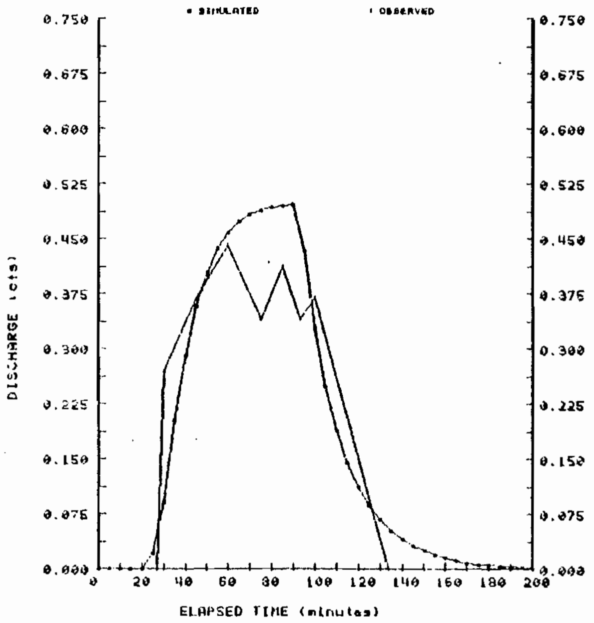


FIG. 7a. SIMULATED VS. OBSERVED HYDROGRAPHS FOR 3/3/82.

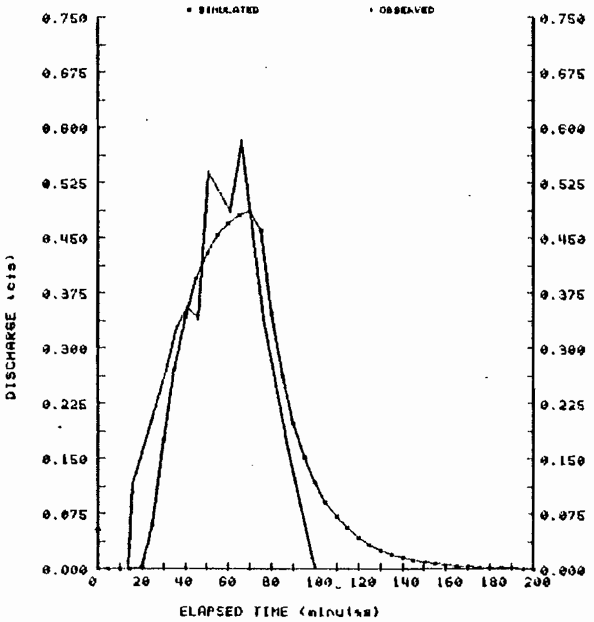


FIG. 7b SIMULATED VS. OBSERVED HYDROGRAPHS FOR 3/18/82.

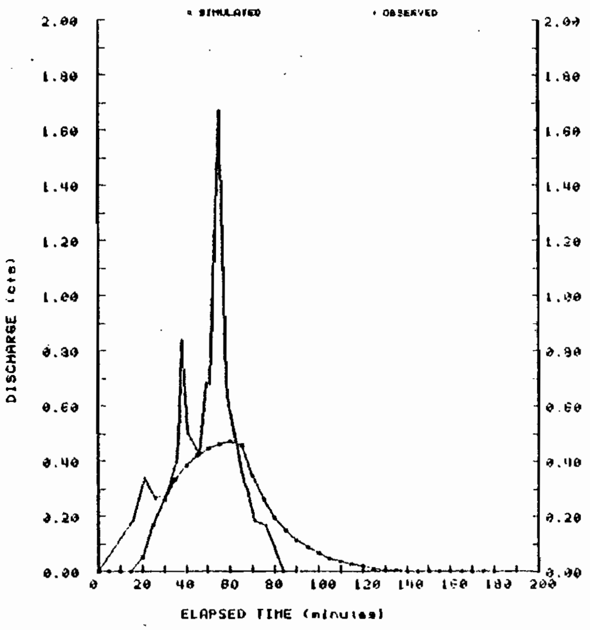


FIG. 7c SIMULATED VS. OBSERVED HYDROGRAPHS FOR 4/4/82.

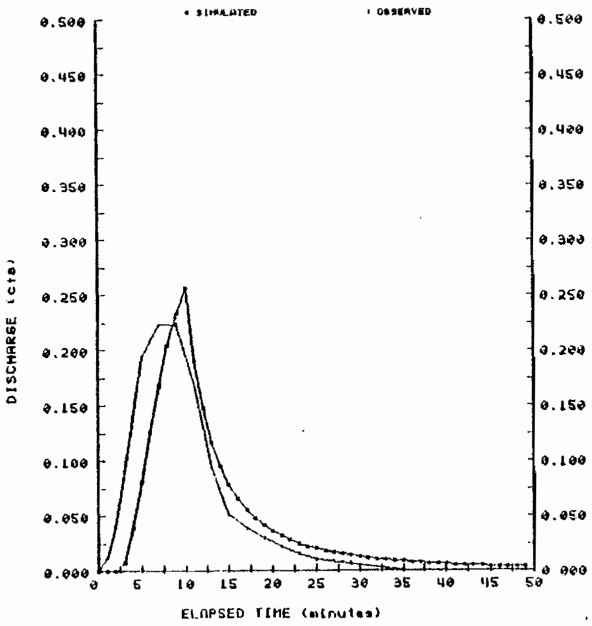


FIG. 8a SIMULATED VS. OBSERVED HYDROGRAPHS FOR 5/11/82.

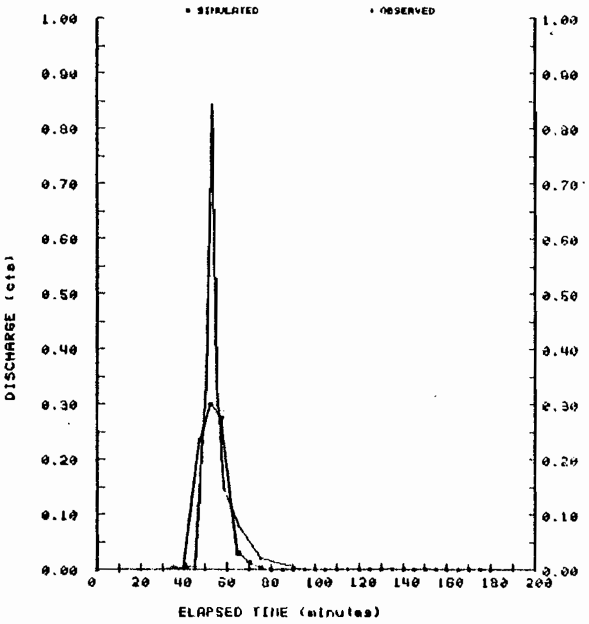


FIG. 8b SIMULATED VS. OBSERVED HYDROGRAPHS FOR 6/3/81.

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