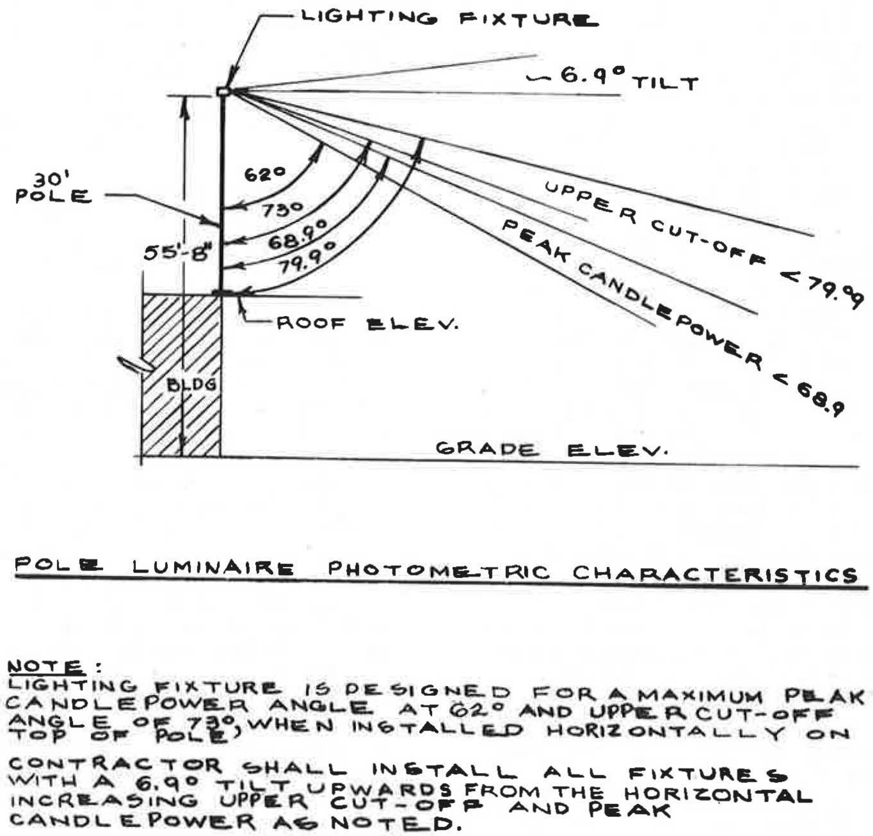
Figure 3. Pole fixture photometric characteristics, apron and ramp lighting, Chicago-O'Hare International Airport.



As far as visual impact is concerned, the new prototype lighting, which was installed with the cooperation of American Airlines, has made a dramatic difference at Gate K-8. The ground crews are enthusiastic, stating that they went without accidents and can pursue their tasks readily since the new lighting was placed in service.

After six months of continuous operation of the lights, no complaints were received from the pilots and no real problems regarding day or nighttime visibility are anticipated from the air traffic or ground controllers. Requests for similar lighting at the remaining gates are now being made.

MATHEMATICAL MODEL OF RUNOFF FROM GROOVED RUNWAYS

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Abstract

A conceptual model of runoff from grooved runways based on a hydraulically equivalent ungrooved surface has been investigated for its capability to simulate flow depths on a runway surface. The specific objective of model development is to predict runoff characteristics for uniform rainfall rates on a 100-foot wide concrete runway, grooved and sloping traversely at 1-1/2 percent. A FORTRAN IV computer program is used to solve the kinematic wave approximation to the shallow water equations which are central to the model. The kinematic wave approximation is employed for various hydraulic roughnesses as predicted from another study using a typical maxrotexture range of 0.01 inch to 0.03 inch. A rectangular groove shape with fixed dimensions is considered at five different spacings. The computer simulation results show that grooving enhances the drainage from the pavement in the form of decreased surface depths. The maximum depth reduction due to grooving is about 19 percent for all rainfall intensities, including the 6 inch per hour maximum in this study. These results are tentative, since an experimental study involving equipment that simulates rain on an indoor slab is presently underway. Qualitative observations of early experimental runs seem to indicate that depth reductions based on computer model runs may be too small.

Introduction

The landing aircraft is brought to a quick stop by the combined forces of aerodynamic drag, reverse engine thrust, and wheel braking. The stopping distance can vary widely depending upon the friction level available at the tire-runway interface. When this interface is dry, the friction level is high and the aircraft can be brought to a stop quickly; however, the presence of water at the interface reduces the available friction level significantly, and potentially hazardous conditions of overrun and hydroplaning exist.

During hydroplaning, the aircraft tire is physically separated from the runway surface by a layer of water that supports the aircraft weight by developing hydrodynamic and viscous pressures within the water layer. The friction forces at the tire-runway interface approach zero during hydroplaning. A relief in the fluid pressures is necessary to bring about a contact between the aircraft tire and the runway surface for developing higher friction forces at the interface. Partial relief in the pressures can be provided by cutting circumferential grooves on the aircraft tire and transverse grooves in the runway surface which also provide improved drainage.

Pavement grooves have been extensively studied by the National Aeronautics and Space Administration (NASA) (1) and by the Federal Aviation Administration (FAA) (2). Both the NASA and the FAA have concluded that smaller groove spacings provide higher friction levels to a braking aircraft on wet to flooded runways. The FAA has further shown (3) that the grooves spaced at 3 inches or less will provide an "acceptable" performance to an aircraft on water-covered surfaces, and the installation cost of these grooves can be significantly less than that of the grooves spaced at 1-1/4 inches.

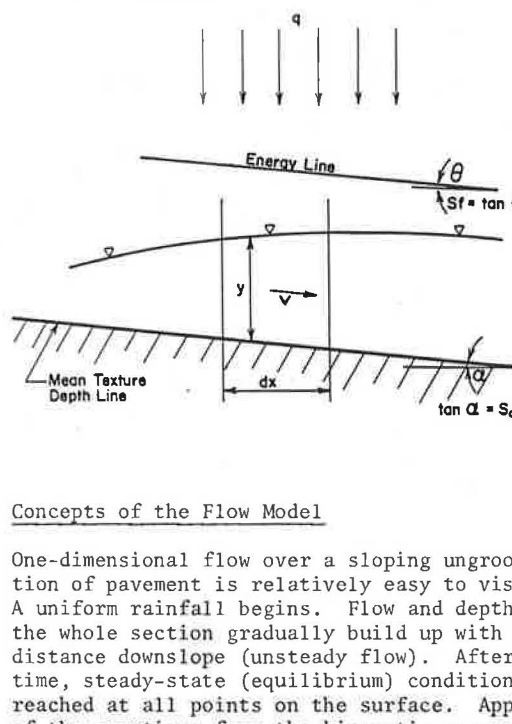
The improved braking performance on a grooved runway is believed to be the result of a dual process of water removal. First, the grooves influence the surface water drainage by providing smooth channels through which water can flow freely. Whether decreases in groove spacing will continually improve the drainage on the runways is not known. The smaller groove spacing will create more flow area and thus more flow per unit length, but a larger spacing might be equally effective and certainly less expensive. Groove spacing, surface texture, and slope of the runway are interrelated in establishing the free flow of water. Second, the grooves provide forced water escape from the tire runway interface when the aircraft is decelerated on a watercovered runway. Since the maximum amount of water that can be removed from the runway in a given time is limited, both the free flow and forced escape of water are important.

The relative improvement in the braking performance of an aircraft resulting from forced water escape in grooves of various spacings was established in Reference 2. The results indicated that an increase in groove spacing causes reduction in available friction level. The effect of groove spacings on the free flow of water on a runway is the subject matter of the research which is central to this paper.

The main direction of drainage from runways is parallel to the grooves, so that the term "lateral flow" to the grooves refers to local flow normal to the grooves and parallel to the flight path. While it is generally known that grooving enhances surface drainage, it is important to identify and measure the significant factors that affect drainage efficiency on a paved runway. To meet these objectives, the research was divided into two phases. In Phase I, a mathematical model was developed which included the pertinent parameters for grooved pavement runoff. A Phase II experimental study involving equipment that simulates rain on an indoor 30 feet by 15 feet slab is now underway to test and correct the model within the constraint that the 30-feet length plays the role of the 100-feet width of a runway. The sprinkler equipment was developed specifically for a 30 feet x 15 feet area in a separate but cooperative study. This paper presents results from Phase 1 (4).

The mathematical model was developed from one of three concepts using the kinematic wave approximation to the shallow water equations for grooved and ungrooved runways with zero longitudinal slopes. Mathematical details of this approximation and the equations are discussed later in this paper. In all cases the assumption is made that rain falling on the pavement drains freely from the edge of the pavement, except for water that either is stored in grooves or merely contributes to the wetness of the pavement. In the results presented herein, grooves are assumed to run through the edge of the pavement. However, the model will handle the commonly occurring case where grooves do not run out to the edge of the pavement. One can visualize that water can spill out of the ends of these sloping grooves onto the ungrooved portion of the pavement. Flow can then exit from the pavement edge at the same depth it would have on an ungrooved runway. The numerical solutions of the model were generated by a FORTRAN IV computer program. Hydroplaning analysis was not within the scope of this research, even though the results herein are important to the topic. Discussion of hydroplaning may be found in publications such as Agrawal and Daiutolo (5) and Horne (6).

Figure 1. Definition sketch of overland flow on a plan surface.



Concepts of the Flow Model

One-dimensional flow over a sloping ungrooved section of pavement is relatively easy to visualize. A uniform rainfall begins. Flow and depths over the whole section gradually build up with time and distance downslope (unsteady flow). After a short time, steady-state (equilibrium) conditions are reached at all points on the surface. Application of the equations from the kinematic wave approximation occurs smoothly, efficiently, and as accurately as estimates will permit. Maximum values of depth and flow exit at the downstream end of the pavement. A definition sketch for overland flow is shown in Figure 1.

Flow over the grooved pavement is almost as easy to visualize, with unsteady conditions followed by equilibrium conditions. Application of the one-dimensional kinematic wave equations does not occur smoothly, however, since some water will flow into the grooves. This lateral inflow will occur at a faster rate further downstream where larger depths (heads) are available, and will add to the flow the grooves carry due to rain falling directly into them. At some point the grooves fill up, and flow apparently occurs over the surface in a manner similar to that on the ungrooved surface, although at lower depths. Three modelling concepts have been used to represent this process. All three concepts have merit and are described in the following paragraphs in the sequence in which they were studied. The "wetted perimeter" concept is described last since the results of this study are based on it.

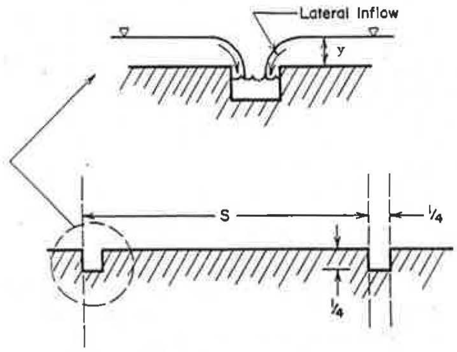
Initially, a mathematical model for the grooved pavement was attempted by using a side-channel weir equation to estimate the lateral inflow. Execution of the computer program for this model appeared successful until conservation of mass (continuity) was checked. The flow leaving the pavement was less than the total flow occurring due to rainfall onto the pavement. After several refinements, the error was reduced to 6 percent, but further study was unsuccessful and the model was set aside due to time restrictions.

A second effort was attempted, in which all of the rain falling on the pavement at the upstream end was matched to the total volume of the grooves to estimate where the grooves would fill. Once this location was established, computations were executed beginning there as though the pavement was ungrooved, except that the flow in the full grooves was accounted for. A small continuity error of about 0.5 percent was found, perhaps due to roundoff. This model was set aside because it seemed unrealistic. It is difficult to imagine completely filled grooves at the upstream end of the pavement with no flow on the adjacent textured pavement. Also, at the extreme upstream edge, there would not be sufficient water to fill the groove. Recent experimental runs with the rainfall simulater on the grooved slab seem to indicate that on the upstream portion of the slab, virtually all of the rainfall flows laterally into the grooves with no apparent flow on the adjacent textured surface. However, the grooves remain unfilled for quite some distance despite carrying all the flow.

A third model was developed which seemed to minimize these problems. The model is built on the concept of wetted perimeter, i.e., the total linear length of the solid boundary of a cross section through which flow can occur. The wetted perimeter is the primary factor related to the boundary shear stress caused by the flow of water over the surface. The model assumes a planar ungrooved boundary which has a width equivalent to the wetted perimeter of a grooved boundary, thereby preserving the shear area. In Figure 2, for example, which shows the size and spacing, s, of the rectangular groove pattern considered in this paper, the width of the equivalent planar section corresponding to s is (s + 1/2 inch). Thus, a segment 3/4 inch in width models the groove on this planar section. Rain still falls into the middle 1/4 inch of this segment, but the rain falling on the additional 1/4 inch on each side of the segment is also considered to be carried in the groove as an arbitrary allotment of lateral inflow from adjacent surfaces. Hence, there is available water to be carried on the adjacent textured surface, but less in amount than on an ungrooved pavement. A computer program executed this model successfully, with continuity exactly satisfied. The program adjusts the rainfall rate internally in the solution so it is equivalent to the actual rate on the narrower width. The results of these computer runs are the basis of the analysis presented in this paper.

This model is not without weaknesses. The grooves probably have a smaller hydraulic resistance (Manning's n) than the adjacent textured surface

Figure 2. Pavement groove pattern included in computer analysis.



Rectangular Groove Pattern (Dimensions in inches)
S = ∞, 5 in., 21/2 in., 1-1/4 in.

due to polishing while being saw cut. Hence, some weighted average n may eventually be necessary in the model. Also, the allotment of lateral inflow into a groove from adjacent surfaces is based solely on how much larger is the wetted perimeter of a groove compared with its top width. The rectangular groove shown in Figure 2 has a wetted perimeter three times its top width; however, the wetted perimeter of other shapes may not be in that same proportion. One would think that lateral inflow would be independent of groove shape, but the arbitrary allotments of lateral inflow to different shapes will be different. Early experimental results seem to indicate that arbitrary allotments based on the wetted perimeter are far too conservative. Eventual correction of the mathematical model is anticipated when the model is applied to the actual situation of flow over the grooved pavement on the experimental slab.

Background For Conceptual Models

The equations for predicting water thickness on an overland flow surface, such as a sloping pavement, are known as the shallow water equations. These equations are based on conservation of mass and momentum during unsteady, spatially varied flow, and have the one-dimensional form shown in Henderson (7) or Chow (8):

$$\text{Continuity:}\quad \frac{\partial y}{\partial t} + v\frac{\partial y}{\partial x} + y\frac{\partial v}{\partial x} = q \qquad (1)$$

$$\text{Momentum:}\quad \frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + g\frac{\partial y}{\partial x} = g(S_o - S_f) - \frac{q}{y}(v - u) \qquad (2)$$

where

- v = local velocity in fps
- y = local depth in feet
- g = gravitational acceleration constant
- q = lateral inflow in rainfall excess rate in feet^3/s/feet of length
- S_o = slope of plane or channel in feet/feet
- S_f = friction slope in feet/feet
- u = velocity of lateral inflow in fps
- x = distance downstream in feet
- t = time in seconds.

Again, reference is made to the variables shown in

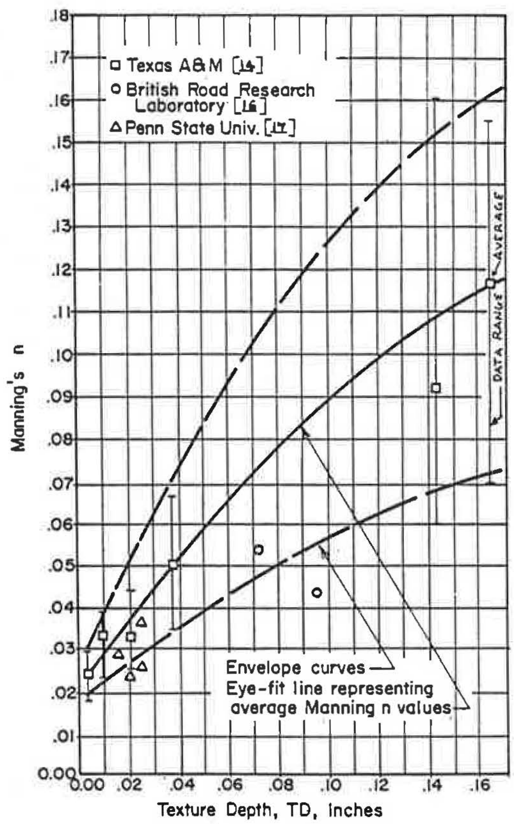


Figure 3. Relationship between texture depth and Manning roughness; coefficient based on measured water depths (15).

Figure 1. These equations have been applied to many problems of open-channel flow, including the analysis of flood wave movement in river systems. Their solution on the computer requires the use of complex finite-differencing methods which are time-consuming and sometimes numerically unstable, as Liggett and Woolhiser (9) have indicated.

Many investigators have examined the properties of the kinematic wave solution as an approximation to the complete shallow water equations. Typical results are given by Lighthill and Whitham (10). The kinematic approximation is generally valid when the friction forces on the plane or channel are just balanced by the gravitational forces, and the velocity terms in equation (2) become negligible. Under these conditions, equation (2) reduces to $S_o = S_f$, and the Chezy or Manning formula (described later) can be used to describe the resulting flow. Woolhiser and Liggett (11) in particular have tested kinematic solutions for the rising hydrograph on an overland flow plane and have concluded that many cases of overland flow can be represented by the mathematically simpler kinematic wave approximation.

Numerous studies of the kinematic wave equation have been completed since the late 1960s, and this simplified approach has been almost universally accepted for the analysis of surface runoff and overland flow from paved surfaces. Kibler and Aron (12) have applied a kinematic wave runoff model to the controlled laboratory runoff studies of Izzard (13) for various pavement surfaces. Their simulated runoff agrees closely with the measured Izzard runoff under changing rainfall supply rates at two different values of Manning's roughness (n).

Gallaway, Schiller, and Rose (14) have correctly identified the pavement runoff factors as rainfall intensity, pavement texture, cross slope, and flow length, and have incorporated these in an empirical expression for average water film above the top of the texture. Although their study is valuable as a background for the present study, it does not account for pavements that are grooved, nor does it indicate a basic measure of flow resistance, such as Manning's n, which is vital to a kinematic wave solution. Reed and Kibler (15) have used data from this and other studies (16), (17) to calculate Manning's n and subsequently to investigate its prediction. Some of their results are shown in Figure 3. The average Manning n value curve will be used in this paper to estimate Manning's n, although use of the upper curve would generate conservative results. The texture depth can be obtained from macrotexture measurements which are typically described in Rose et al. (18) and Henry and Hegmon (19). Representative values of Manning's n were selected for the analytical model in this study, based on typical runway macrotexture between 0.01 inch and 0.03 inch.

In their study, Reed and Kibler (15) have used conditions described later to justify their use of the kinematic wave approximation as well as the use of the Manning equation, which primarily applies to fully turbulent flow.

Basic Equations for Overland Flow and Paved Surfaces

Overland flow is analogous to the flow that would occur in an impervious open channel of very great width. Even though the runoff depths are small, the flow is likely to be turbulent because of the pelting rain, a view supported by the Army Corps of Engineers (20). The hydraulics of overload flow are generally described by the kinematic approximation to the complete shallow water equations, equations (1) and (2). It has been shown (11) that the kinematic wave approximation to these equations is generally valid when the parameter K exceeds 20 and the Froude number F_o, exceeds 0.5:

$$K = \frac{S_o \cdot L_o}{Y_o \cdot F_o^2} \tag{3}$$

where

S_o = slope of flow path, feet/feet

L_o = total length of flow path, feet

Y_o = normal depth at end of flow path, feet

F_o = Froude number = $V_o/\sqrt{gY_o}$

V_o - normal flow velocity at end of flow path, feet/s

= $(q \cdot L_o)/Y_o$

q = lateral inflow or rainfall excess rate in feet/s

g = gravitational constant = 32.2 feet/s^2.

Under subcritical flow conditions where F_o is less than 0.5, an additional criterion must be met: $F_o^2\ K = S_o\ L_o/Y_o > 5$ (21).

Except on extremely flat slopes with intense rainfall, most cases of overland flow on paved surfaces, including the ones in this paper, will fall easily into the kinematic range based on the preceding criteria. This means that the more complex equations for spatially varied unsteady flow can be replaced by the simpler equations involving mass continuity and uniform flow. The partial differential form of the kinematic equation is well known and has been used frequently for overland flow modelling in urban watersheds (22). Integrating the characteristic equation in an x-t plane under constant rainfall condition yields a simple relation for the equilibrium flow depth (Y_{eq}) at different points in the downstream direction:

$$Y_{eq} = q\ t_{eq} \tag{4}$$

where q = lateral inflow or rainfall excess rate in cfs/$feet^2$

t_{eq} = equilibrium flow time, s.

The equilibrium flow time, t_{eq}, on an inpervious surface under constant rainfall rate, q, is determined by the equation:

$$t_{eq} = \frac{1}{q}\left[\frac{Lq}{\alpha}\right]^{1/m} \tag{5}$$

where L = length along flow path or half-width of runway, feet

α, m = parameters of the hydraulic friction relationship.

Under kinematic flow conditions, the friction or energy slope, S_f, is equal to the slope of the plane, S_o, and this permits the use of a simplified flow velocity relation of the form:

$$V = \alpha\ Y^{m-1} \tag{6}$$

where V = flow velocity, feet/s

Y = flow depth, feet.

For turbulent flow on an overland surface, the parameters α and m can be determined from the Manning equation as

$$\alpha = \frac{1.49}{n} S_o^{1/2} \text{ (English units)} \tag{7}$$

$$m = 5/3 \text{ (dimensionless constant).}$$

Equations (4), (5), (6), and (7) provide the theoretical basis for the flow model described earlier in this paper.

Equation (7) can now be applied to equation (5) for t_{eq} to obtain

$$t_{eq}(\text{sec}) = \frac{56.25\ L^{0.6}\ n^{0.6}}{i^{0.4} S_o^{0.3}} \tag{8}$$

where i = rainfall intensity in inch/hour

n - Manning roughness coefficient

and the other terms are as defined earlier. Equation (4) for Y_{eq} can now be written

$$Y_{eq}(\text{in.}) = \left[\frac{n\ L\ i}{1023\ S_o^{0.5}}\right]^{0.6} \tag{9}$$

Discharges under uniform rain can now be computed for all points L feet downstream using

$$Q = \alpha\ Y^m \tag{10}$$

where Q = discharge, cfs/feet

and the other terms are as defined earlier. Equilibrium flows can also be obtained from continuity considerations by calculating inflow onto the pavement from upstream intensity. Equations (8), (9), and (10), together with (6) and (7), provide the computational basis for the FORTRAN IV program written to execute the flow model.

Henderson (7) has suggested that fully turbulent flow conditions prevail when

$$n^6 \sqrt{R_h S_f} \geq 1.9 \times 10^{-13} \tag{11}$$

where R_h = hydraulic radius (assumed equal to overland flow depth, Y)

S_f = friction slope ($S_f = S_o$) under kinematic flow conditions.

Equation (11) is satisfied in the present study for the most severe case of the data used, allowing for some reasonable minimum depth such as 0.02 inch. Hence, the use of the Manning equation to describe the friction relations for the pavements in this study is justified. For Henderson numbers less than 1.9 x 10^{-13}, the flow is transitional or laminar, and consequently the Manning n should not be used unless it includes the Reynolds number (23).

Computer Program To Solve The Model

A FORTRAN IV program was written to solve the mathematical flow problem previously described. The program was executed on an IBM 370/Model 3033 system to generate the results which will be depicted graphically in this paper. The output of the program could be virtually limitless when one considers the wide range of values that could be used for the pertinent parameters. Even when the parameter ranges are limited to realistic values for the problem studied, the output can still be in excess of what is needed.

The study considered only the square groove (rectangular) with fixed dimensions and variable spacing, s, as shown in Figure 3. In addition, five different intensities, i, of 1, 2, 3, 4 and 6 inches/hour, and three different macrotexture depths, TD, of 0.01, 0.02, and 0.03 inches were considered. Figure 3 was used to determine Manning's n from the average curve.

Graphical Presentation Of Results

Figures 4 through 7 are representative graphical displays of the computer solution of the mathematical flow model. Although the graphs summarize the results succinctly, not all of the output generated in this study has been shown. All of the figures were plotted using a Hewlett-Packard graphics terminal which selects appropriate scales for the axes. The scales are not always convenient from the standpoint of good plotting practice. Axes are labeled in word descriptions, since the plotting was done prior to selecting symbols for some of the

Figure 4. Effect of variable rainfall rate on water depth, Y_{eq}, for ungrooved surface.

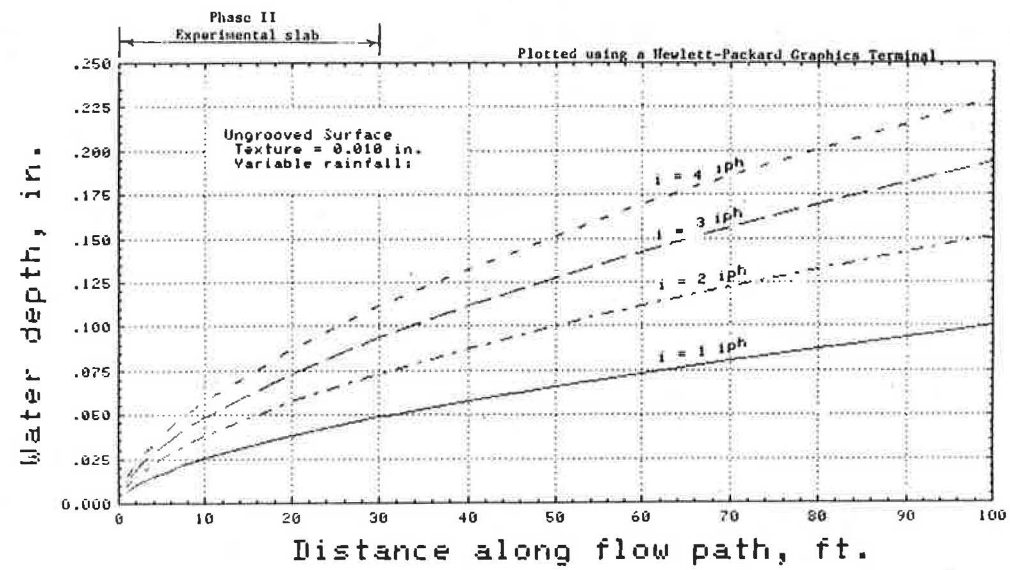


Figure 5. Effect of variable texture depth, TD, on water depth, Y_{eq}, for ungrooved surface.

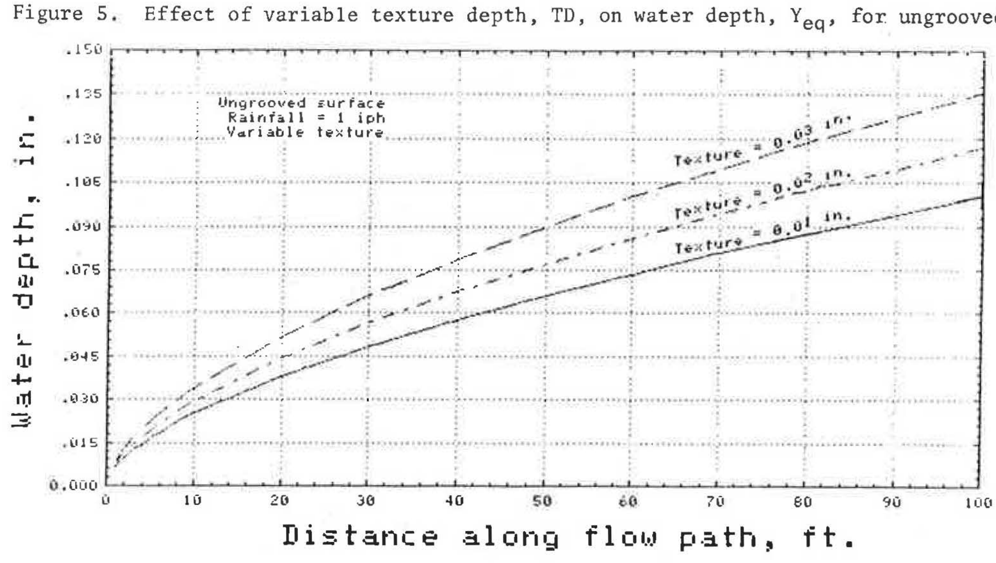


Figure 6. Effect of variable rainfall rate on water depth, Y_{eq}, for grooved surface at s = 2.5 inches.

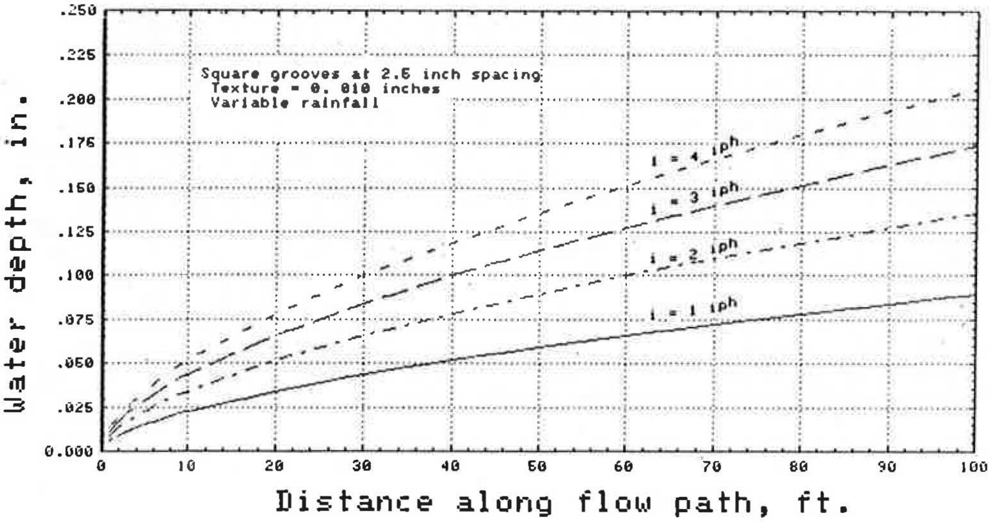
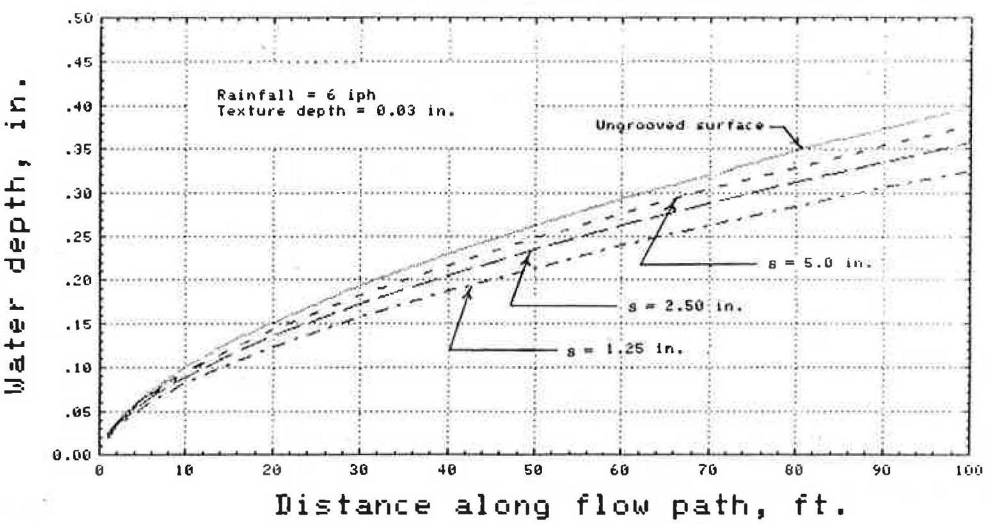


Figure 7. Effect of variable groove spacing, s, on water depth, Y_{eq}, at high intensity.



quantities. Some symbols do show up however, except for length of flow path which is represented by L. The 6-inch/hour intensity was chosen as the maximum for this study because, together with the length of flow path which is related to rainfall duration, it statistically represents a storm with a return period of about 25 years in Pennsylvania. Such a storm is typically used to estimate design flows for storm drainage systems.

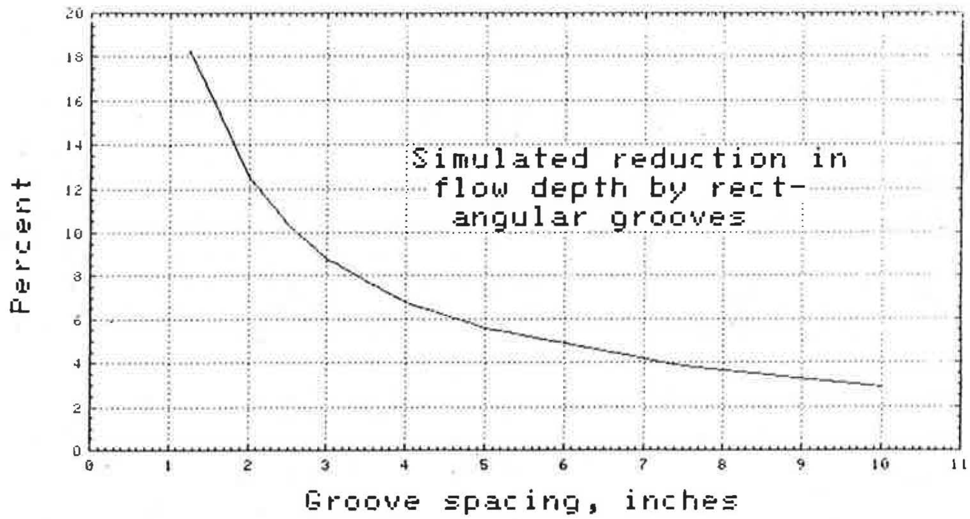
Discussion and Conclusions

Conclusions at this stage in the study, without the support of experimental data, are somewhat speculative. Even when experimental data become available, any conclusions will be limited to rectangular grooves on a 30-feet slab for the flow path. Nevertheless, it may be observed from the analytical results that the flow model does in fact produce expected trends of the variables. For example, as might be expected, it is evident from Figures 4-7 that:

1. Water depths increase downstream with distance along the flowpath.
2. Water depths increase with increasing rainfall intensity.
3. Water depths increase with increasing texture depth (flow resistance).
4. Water depths decrease with decreasing spacing of grooves.
5. The largest water depth (0.4 inch) occurred at the downstream edge of the ungrooved pavement, at the largest values of texture depth (0.03 inch) and intensity (6 inch/hour) used in the study.

It should be noted that any observations made about water depths above the surfaces adjacent to the grooves can probably be made about flows there also, as equation (10) will attest. Of course, the total flow is made up of the sum of flows on the surface and in the grooves, and one observation is certain: the total flow off the pavement at any L

Figure 8. Effect of groove spacing in analytical model on reducing water depths, Y_{eq}, for all rainfall rates, textures, and locations.



must equal the total flow raining onto the pavement under equilibrium conditions. The mathematical model satisfied this continuity principle (conservation of mass) for all of the computer runs made for a given rainfall rate and L, independent of the grooving condition or the texture of the pavement.

The curve on Figure 8 shows how decreased groove spacing in the analytical model reduces the equilibrium flow depths over the ungrooved pavement surface. The curve was plotted using a Hewlett-Packard graphics terminal from values extracted from several computer output runs. Originally, it was thought that the curve was not general, since it was plotted for particular values of rainfall intensivy, texture depth, and distance along the flow path (L). Spot checks at a random selection of these conditions, along with a careful analysis of the model equations reveal that the curve is general. Caution should be exhibited in emphasizing the results of Figure 8, since the model has not been verified experimentally.

Corresponding reductions in the runoff flow rates carried on the ungrooved pavement are not shown in Figure 8 because depth reduction is more important to a hydroplaning viewpoint. Certainly, as the number of grooves increases, the percentage of the flow carried on surfaces adjacent to the grooves decreases. The percentage of reduction, however, is not general for a given spacing. For example, for s = 1.25 inches, i = 6 inches/hour, L = 100 feet, and TD = 0.03 inch, the reduction is about 11 percent. For s = 1.25 inches, i = 1 inch/hour, L = 100 feet, and TD = 0.01 inch, the reduction is about 43 percent.

In summary, and without experimental confirmation, it appears from Figure 8 that grooved pavement enhances drainage in the form of decreased surface depths. The maximum reduction in depths occurs at s - 1.25 inches and is about 19 percent, which appears to be independent of the magnitude of the depth being reduced, probably due to the particular analytical model being used. Figure 7 alludes to this point also by showing how closely the curves are bunched across water depths for all of the groove spacings at the maximum intensity. The enhancement of drainage in the form of percentage of reduced flow rates is greater at the lower intensities where it is not as important. The authors believe that one of the chief advantages of grooving is the quick drainage of the pavement after the rain has stopped, a point also made by Horne (24). This advantage is especially important for depressed pavement sections where ponding can occur. Very early experimental results indicated that textured surface depth reductions predicted by the model for grooved pavement as shown in Figure 8 may be too small.

Acknowledgments

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