NONDIMENSIONAL ANALYSIS OF SPATIALLY VARIED FLOW IN RECTANGULAR CHANNELS

by

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111. INTRODUCTION

Open channel flow where the discharge of a steady flow is nonuniform along the channel is known as spatially varied flow. This type of flow is encountered in roadside gutters, side-channel spillways, washwater troughs in filters, effluent channels around sewage-treatment tanks, and main drainage channels and feeding channels in irrigation systems.

When the nonuniform flow results from water being added along the course of flow, an appreciable amount of the energy loss comes from the turbulent mixing of the added water and the water flowing in the channel. Since the energy loss is difficult to estimate accurately, the law of conservation of linear momentum is used to analyze this type of flow.

In 1925, Hinds (5) developed a formula, based on the momentum principle, for spatially varied flow with increasing discharge. Other investigators, such as Stein (9), Farve (4), Beij (1), Camp (2), and Li (8), have also applied the momentum principle to the design of channels with spatially varied flow. Since the resulting equations require step-by-step calculations to obtain water surface curves, one-step approximations have generally been acceptable in engineering practice.

Hubbard (6) developed a nondimensional form of the basic equation and solved this equation for the dimensionless profiles for rectangular channels having a small slope and a free overfall at the downstream end of the channel. From the dimensionless profiles, water surface curves may be obtained for a wide range of discharge. By experimentally obtaining flow profiles for a rectangular channel of varnished plywood, with an assumed Manning roughness coefficient of 0.01, he reasonably verified his nondimensional method.

This study is concerned with the application of such a nondimensional equation to rectangular channels of various roughness values. A digital computer program is included for solving the nondimensional equation when the inflow is uniform along the channel axis. Experimental verification of the nondimensional form of the basic equation is included for rectangular channels having Manning roughness coefficients of approximately .008, .013, and .016.

This study is also concerned with the application of a nondimensional form of the basic equation to rectangular channels where the added flow along the channel axis is not uniform. Another digital computer program is included for solving the nondimensional equation when the inflow varies linearly from zero at the upstream end to a maximum at the channel mid-section and back to zero at the outlet. The maximum value, at the middle of the channel, of the inflow is assumed to be equal to the total discharge divided by the channel length.

IV. REVIEW OF LITERATURE

The hydraulic behavior of uniform and nonuniform flow in an open channel can be analyzed by either the law of conservation of energy or the law of conservation of linear momentum. Whenever the energy losses are of relatively high magnitude and uncertainty, the law of conservation of energy is not useful. However, the law of conservation of momentum is applicable and has been applied to such problems.

When water is added along the course of flow, the hydraulic behavior of the resulting nonuniform open channel flow is quite different from that of a channel with uniform flow. The energy lost in uniform flow results from frictional and form resistance. The law of resistance for nonuniform flow is at variance with the laws that have been applied to uniform flow. (7)

In open channels where spatially varied flow exists, the added water causes disturbances in the energy content of the flow. The turbulent mixing of the added water with the water flowing in the channel accounts for an appreciable portion of the energy loss. Since there is no accurate method for determining the energy loss from this mixing, the law for conservation of linear momentum is used to analyze the hydraulic behavior of spatially varied flow with increasing discharge.

This type of spatially varied flow is frequently encountered in engineering practice. Some examples where this type of flow exists include, wash-water troughs in filters, effluent channels around sewage-treatment tanks, and side-channel spillways. Although the high energy losses seem to make such channels hydraulically inefficient, physical conditions sometimes make them desirable.

Hinds (5) was probably the first to develop a substantially correct form of the fundamental differential equation for spatially varied flow with increasing discharge. He was concerned with the disturbed flow condition in side-channel spillways. Since the energy losses in side-channel spillways are usually large, and the relative amounts are dependent on the magnitude and form of each installation, the development of his equation is based on the law of conservation of linear momentum. In deriving the equation, Hinds considered the problem of water entering at exactly right angles to the channel axis. His equation was applicable to channels of any shape with constant incremental flow along the channel axis. He also assumed that the loss of energy due to friction was negligible. The condition of impact and shock loss that exists along the channel was taken into consideration by making the momentum after impact equal to the momentum before impact plus any acceleration due to external forces. Accordingly, Hinds developed the following equation for use in designing new channels when the relationship between Q, V and x is known.

$$y = \frac{1}{g} \int_0^x \left(V \frac{dV}{dx} + \frac{bV^2}{Q} \right) dx \qquad \ldots (1)$$

where

y = ordinate to the water surface curve.

g = acceleration of gravity.

x = total length of channel.

dx = distance between two sections under consideration.

V = velocity at upstream section.

dV = difference in velocity between the sections under consideration.

b = weir discharge per unit length.

Q = discharge at upstream section.

Hinds also developed equation (2), an alternate form of equation (1), for investigating existing channels where the inflow may not be constant.

$$\Delta y = \frac{Q_1}{g} \frac{(V_1 + V_2)}{(Q_1 + Q_2)} \left(\Delta V + \frac{bV_2 \Delta x}{Q_1}\right) \quad \ldots .(2)$$

where

Δy = finite difference in water surface elevation between two sections being considered.

Q_1 and V_1 = discharge and velocity at upstream section, respectively.

and

ΔV and Δx are finite differences in velocity and distance, between two sections under consideration, respectively. The determination of the water surface curve can be obtained by using equation (2) when the location of a control section is known. The solution requires an iterative process for each succeeding increment of channel length.

Farve (4) developed a general method for calculating the water surface curve which included a friction term and a component of inflow velocity in the direction of the channel axis. This method was applied to four variations of the proposed spillway design for Boulder Dam, and the results obtained from each calculation were checked by model tests. Farve's method also requires a step-by-step calculation of the water-surface curve, based on equation (3).

$$\Delta Z = \frac{U_m^{\ 2}}{K^2 R_m^{\ 4/3}} \Delta x + (1 - \frac{u^*}{u_m}) \frac{Q_2^{\ 2} - Q_1^{\ 2}}{2g\ S_m^{\ 2}} + \frac{U_2^{\ 2} - U_1^{\ 2}}{2g} \quad ...(3)$$

where

Δx = horizontal distance between two sections under consideration.

ΔZ = difference in water surface elevation (ΔZ is negative when water level falls in direction of flow).

U_m = mean value of flow velocity.

R_m = mean value of hydraulic radius.

S_m = mean value of wetted section.

Q_1 and U_1 = Quantity of water and mean velocity at upstream section, respectively.

Q_2 and U_2 = Quantity of water and mean velocity at downstream section, respectively.

u^* = component, paralled to direction of flow, of the flow velocity entering at the sides.

g = acceleration of gravity.

K = coeffecient, in the formula for steady flow, depending on the character of the channel bed.

The right hand side of the equation (3) contains, a term for frictional loss, a term for the influence of the change in velocity, and a term for the drop caused by a change in the quantity of flow. To obtain a starting point, the control section is located and critical depth is calculated, as was required for Hinds' method.

Beij (1) developed a series of empirical formulas for flow in roof gutters of various cross-sections. These formulas were applicable when the size of the channel under investigation was no larger than the size of a roof gutter (about six inches by six inches). He also developed an equation, similar to Hinds' equation, for rectangular channels with spatially varied flow. Agreement was poor between Beij's experimental data and values computed by his formula.

Camp (2) developed an equation similar to Farve's except it includes the Darcy-Wiesbach friction factor.

$$\frac{dy}{dx} - \frac{f}{8}\ \frac{V^2}{gR} = \frac{1}{g}(V\ \frac{dV}{dx} + q\ \frac{V^2}{Q}) \qquad \ldots(4)$$

Experimental determination of the friction factor is required. He also developed a method for obtaining water surface curves for channels having sloping walls as well as vertical walls. Water surface curves computed from his equation closely agreed with curves obtained from experimental data.

Li (8) developed a nondimensional form of Hinds' equation to be used in obtaining water surface curves. His equation could be used for determining water surface curves for subcritical and supercritical flow.

The flow was defined through the use of a Froude number. He also obtained experimental verification, using level rectangular channels, of the use of the momentum principle. Sloping rectangular channels were used to obtain experimental verification of his nondimensional equation.

Hubbard (6) developed a nondimensional equation to describe the flow profiles in rectangular channels with spatially varied flow. He solved the equation for various slopes and rates of discharge and concluded that when the slope and roughness are constant the dimensionless profiles are also constant over a wide range of discharge. Tests were conducted on a rectangular channel with various slopes and various discharges that reasonably verified his method. Hubbard used Manning's formula to compute the friction slope.

In applying the Manning formula, the greatest difficulty lies in obtaining the roughness coefficient, n. This requires a method for estimating the resistance to flow in a given channel, which is actually a matter of intangibles. Manning's roughness coefficient, n, varies with such factors as surface roughness, channel irregularities, size and shape of the channel, stage, and discharge. (3) Therefore, it is obvious that the value of n is not actually constant for a given channel, and only approximations for n can be made through the aid of engineering experience. To determine an approximate value of n, uniform flow must be developed in the channel being considered.

Uniform flow is developed when the channel resistance is balanced by the gravity forces. An upstream reach, called the transitory zone, is required to develop uniform flow. In this zone the flow is accelerating and varied. Uniform flow cannot be established if the length of the channel is shorter than the transitory zone. Varied flow may occur again at the downstream end of the channel when the resistance may again be exceeded by gravity forces. The depth of uniform flow is called the normal depth of flow. Open channel flow is uniform when the depth of flow is constant at every section of the channel. Gradually varied flow may be regarded as parallel flow because the change in depth of flow is so mild that the streamlines have neither appreciable curvature nor divergence, i.e., the acceleration component in the cross-sectional plane is negligible. If small slopes are used, the depths of flow may be determined by using piezometer tubes.

V. DIFFERENTIAL EQUATION for SPATIALLY VARIED FLOW

In the theoretical investigation of spatially varied flow with increasing discharge, the following assumptions are made.

1. The flow is considered to be unidirectional. Actually, there may be strong cross currents which result in some lateral uneveness of the water surface. The effects of such cross currents are neglected.
2. Constant and uniform velocity distribution for each cross section is assumed.
3. The curvature of the water surface is small so that the total pressure in the flow is approximately equal to the hydrostatic pressure.
4. The channel bed slope is relatively small. Therefore the effects of the slope on the pressure head and on the force on each section are neglected.
5. The effect of air entrainment is neglected.
6. The friction loss due to shear developed along the channel wall is to be estimated with Manning's formula.

In deriving an equation for spatially varied flow, the following notations are used.

A = Cross sectional area at section 1.

dA = change in cross sectional area between sections 1 and 2.

F_f = frictional force along channel wall between sections 1 and 2.

g = acceleration of gravity.

L = total length of channel.

n = Manning's roughness coefficient.

P = total pressure at the section being examined.

Q = discharge at section 1.

dQ = change in discharge between sections 1 and 2.

R = hydraulic radius of section being examined.

S_f = friction slope in Manning's formula.

S_o = channel bed slope which is equal to sin θ; where θ is the angle between the channel bottom and the horizontal.

V = velocity at section 1.

dV = change of velocity between sections 1 and 2.

w = unit weight of water.

x = distance between upstream end and section 1.

dx = distance between sections 1 and 2.

y = depth at section being examined.

dy = change in depth between sections 1 and 2.

Z = distance from water surface to centroid of the cross sectional area, A.

The momentum principle states that the mass of water flowing multiplied by the accelerating force is equal to the time rate of change of linear momentum. With reference to Figure 1, the momentum passing section 1 per unit time is

$$\frac{w}{g} QV$$

Also, the momentum passing section 2 per unit time is

$$\frac{w}{g} (Q - dQ) (V - dV)$$

Therefore, the time rate of change of linear momentum is

$$\frac{w}{g} QV - \frac{w}{g} (Q - dQ) (V - dV) = \frac{w}{g} (QdV + (V - dV) dQ)$$

If W is equal to the weight of the body of water between sections 1 and 2, the component of W in the direction of flow is

$$W \sin \theta = w S_o (A + \frac{dA}{2}) dx \cong w S_o A dx$$

The frictional force along the channel wall is

$$F_f = w (A + \frac{dA}{2}) S_f dx \cong w S_f A dx$$

where $S_f = \frac{V^2 n^2}{2.22 R^{4/3}}$ as defined by the Manning formula.

The total pressure in the flow, in the direction of flow, at section 1 is

$$P_1 = w Z A$$

Also, the total pressure at section 2 is

$$P_2 = w\ (Z + \frac{dy}{2})\ (A + dA) = w\ (Z + dy)\ A + \frac{w}{2}\ dA\ dy$$

or $P_2 \cong w\ (Z + dy)\ A$

Therefore

$$P_2 - P_1 = w\ (Z + dy)\ A - wZA = w\ dy\ A$$

Applying the momentum principle,

$$\frac{w}{g}\ (Q\ dV + (V{-}dV)\ dQ) = P_2 - P_1 + W \sin \theta - F_f$$

Therefore, substitution of the above equations gives

$$\frac{w}{g}\ (Q\ dV + (V - dV)dQ) = w\ dy\ A + w\ S_o\ A\ dx - w\ S_f A\ dx$$

Solving for dy gives

$$dy = \frac{1}{gA}\ (QdV + (V - dV)\ dQ) + (S_f - S_o)\ dx$$

which is

$$dy = \frac{1}{g}\ (\frac{Q}{A}\ dV + (V - dV)\ \frac{dQ}{A}) + (S_f - S_o)\ dx$$

or

$$dy = \frac{1}{g}\ (VdV + \frac{VdQ}{A} - \frac{dV\ dQ}{A}) + (S_f - S_o)\ dx \qquad \ldots(5)$$

Neglecting the term containing the product of differentials, Equation (5) reduces to

$$dy \cong \frac{1}{g} \left(VdV + \frac{VdQ}{A}\right) + (S_f - S_o)\, dx \qquad \ldots(6)$$

Equation (6) is referred to as the fundamental differential equation for spatially varied flow with increasing discharge.

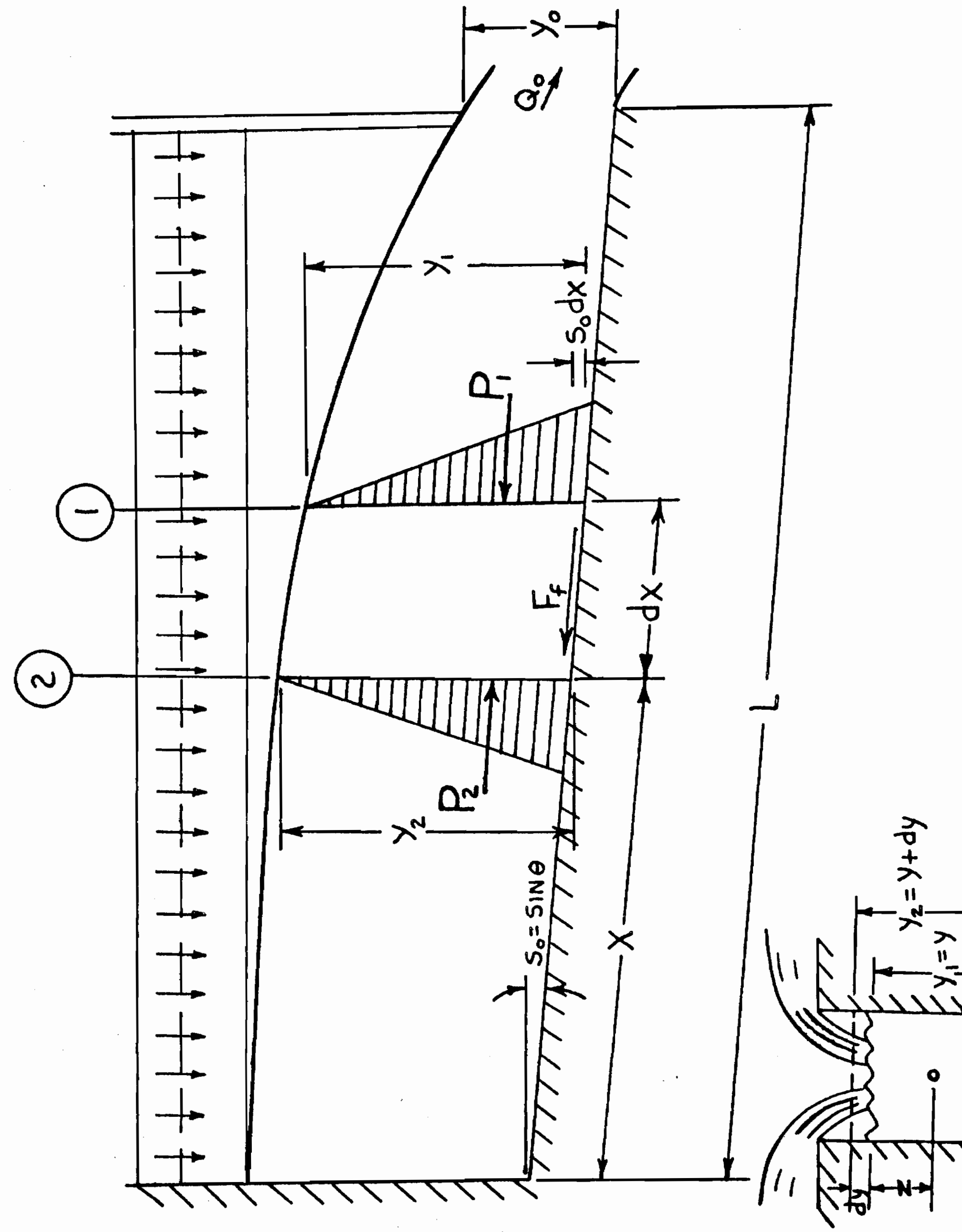

FIGURE 1. SPATIALLY VARIED FLOW DIAGRAM

VI. NONDIMENSIONAL EQUATION DEVELOPED FROM MOMENTUM PRINCIPLE

Equation (7) is an expression of the law of conservation of linear momentum for spatially varied flow.

$$\frac{w}{g}\left(QdV + (V - dV)\, dQ\right) = w\, A\, dy + w\,(S_o - S_f)\, A\, dx \quad \ldots(7)$$

If the differentials are considered as finite differences, equation (7) may be written as

$$\frac{1}{g}\left(Q\Delta V + (V - \Delta V)\,\Delta Q\right) = \bar{A}\,\Delta y + (S_o - S_f)\,\bar{A}\,\Delta x$$

Therefore

$$\Delta y = \frac{1}{g\bar{A}}\left(Q\,\Delta V + (V - \Delta V)\,\Delta Q\right) + (S_f - S_o)\,\Delta x$$

Since $V - \Delta V = V_2$ and $\bar{A} = \dfrac{Q_1 + Q_2}{V_1 + V_2}$, the above equation

may be written as

$$\Delta y = \frac{1}{g}\left(\frac{V_1 + V_2}{Q_1 + Q_2}\right)\left(Q_1\Delta V + V_2\Delta Q\right) + (S_f - S_o)\,\Delta x$$

or

$$\Delta y = \frac{Q_1}{g}\left(\frac{V_1 + V_2}{Q_1 + Q_2}\right)\left(\Delta V + \frac{V_2\Delta Q}{Q_1}\right) + (S_f - S_o)\,\Delta x \quad \ldots(8)$$

In order to nondimensionalize equation (8), the following substitutions are made.

$$\bar{y} = \frac{y}{y_o}\ ;\quad \bar{x} = \frac{x}{L}\ ;\quad \bar{Q} = \frac{Q}{Q_o}\ ;\quad \text{and } \bar{V} = \frac{V}{V_o}$$

or

$$y = \bar{y}\, y_o; \quad x = \bar{x}\, L; \quad Q = \bar{Q}\, Q_o; \quad \text{and } V = \bar{V}\, V_o$$

where the subscript $_o$ denotes critical flow conditions at the outlet.

Therefore

$$\Delta\bar{y}\, y_o = \frac{\bar{Q}_1 Q_o}{g} \left(\frac{\bar{V}_1 V_o + \bar{V}_2 V_o}{\bar{Q}_1 Q_o + \bar{Q}_2 Q_o}\right) \left(\Delta\bar{V}\, V_o + \frac{\bar{V}_2 V_o \Delta\bar{Q} Q_o}{\bar{Q}_1 Q_o}\right)$$

$$+ (S_f - S_o)\, \Delta\bar{x} L \qquad \ldots(9)$$

Equation (9) reduces to

$$\Delta\bar{y}\, y_o = \frac{\bar{Q}_1 V_o}{g} \left(\frac{\bar{V}_1 + \bar{V}_2}{\bar{Q}_1 + \bar{Q}_2}\right) \left(\Delta\bar{V}\, V_o + \frac{\bar{V}_2 V_o \Delta\bar{Q}}{\bar{Q}_1}\right)$$

$$+ (S_f - S_o)\, \Delta\bar{x} L$$

Solving for $\Delta\bar{y}$ gives

$$\Delta\bar{y} = \frac{\bar{Q}_1 V_o^2}{g y_o} \left(\frac{\bar{V}_1 + \bar{V}_2}{\bar{Q}_1 + \bar{Q}_2}\right) \left(\Delta\bar{V} + \frac{\bar{V}_2 \Delta\bar{Q}}{\bar{Q}_1}\right) + (S_f - S_o)\, \Delta\bar{x} \frac{L}{y_o}$$

For rectangular channels, $\dfrac{V_o^{\,2}}{g y_o} = (\text{Froude number})^2 = 1$

Therefore

$$\Delta\bar{y} = \bar{Q}_1 \left(\frac{\bar{V}_1 + \bar{V}_2}{\bar{Q}_1 + \bar{Q}_2}\right) \left(\Delta\bar{V} + \frac{\bar{V}_2 \Delta\bar{Q}}{\bar{Q}_1}\right) + (S_f - S_o)\, \Delta\bar{x} \frac{L}{y_o}$$

Using the same procedure, Manning's formula in non-dimensional form is

$$S_f = \frac{(V_o^{\,2} n^2)}{(2.22 y_o^{\,4/3} K^{4/3})} \frac{(\bar{V}_2^{\,2})}{(\bar{y}_2^{\,4/3})}$$

where $K = \frac{R_o}{y_o}$

The nondimensional hydraulic radius at any section is approximated as $K\ \bar{y}$. This assumes that the nondimensional form of the hydraulic radius changes linearly as the ratio of the depth at any section to the critical depth.

The values of $\bar{Q}$, $\bar{V}$, and $\bar{x}$ vary from zero at the upstream end to one at the outlet. Starting at the outlet and proceeding upstream in equal increments of length, the equation can be solved for $\Delta\bar{y}$ using an iterative method.

VII. INVESTIGATION OF MANNING ROUGHNESS COEFFICIENT

As stated previously, one purpose of this study was to determine the accuracy of the nondimensional equation for spatially varied flow in rectangular channels of various roughness values. Therefore, experimental determination of Manning's roughness coefficients for various rectangular channels was required.

An open channel with continuous flow was set up in the laboratory. The channel was constructed with varnished plywood and had a length of fourteen feet, a width of six inches, and a bottom slope of approximately 0.0025. In order to vary the roughness value of the channel, screen wire and wooden cubes were obtained which could be placed in the channel. The screen wire was 1/4 inch mesh and was tacked to the channel bottom and walls (figure 2). The wooden cubes were made of 3/4 inch plywood and were nailed to the channel (figure 3). The cubes were placed three inches apart along the bottom of the channel in alternating rows of two and three cubes. Cubes were also placed along the channel walls, three inches above the channel bottom and at six-inch intervals, across from the bottom rows with two cubes.

To determine the various roughness values, uniform flow had to be developed in the channel. The depth of flow was measured by means of manometer tubes placed at one-foot intervals along the center-line of the channel bottom. Approximate values for Manning's roughness coefficients were determined for the varnished plywood channel (n = 0.008), the varnished plywood channel with screen wire tacked to the channel (n = 0.013), and the varnished plywood channel with the wooden cubes nailed to the channel (n = 0.016). These coefficients were calculated from the data in Table 3, Appendix B.

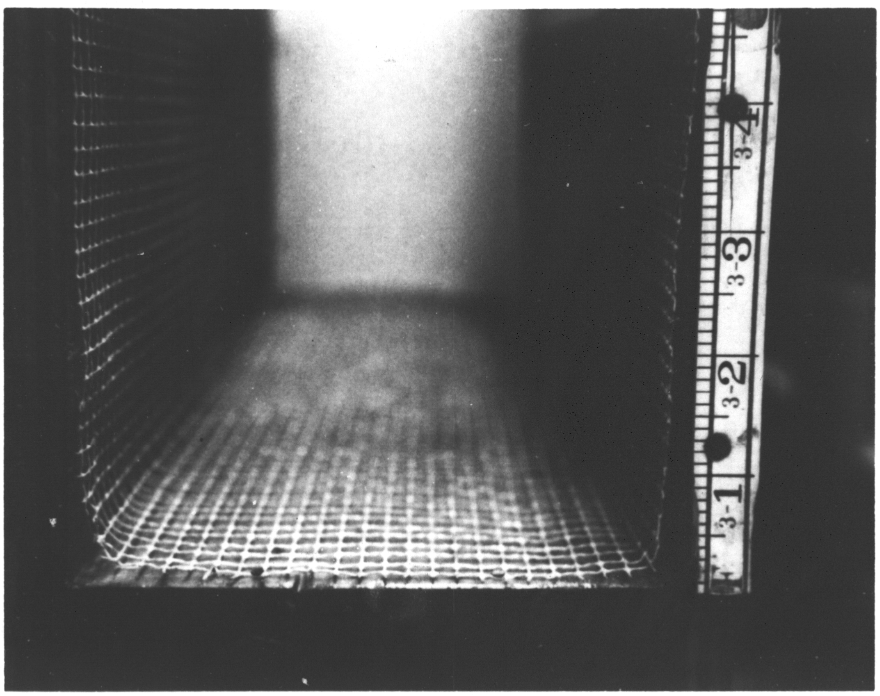

Figure 2. Varnished plywood channel with screen wire, $n = 0.013$.

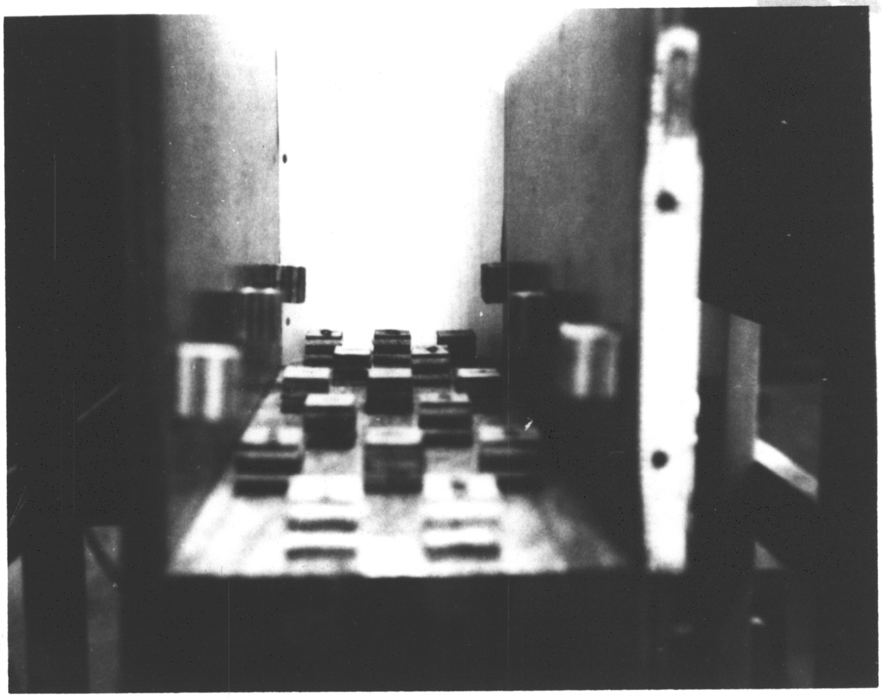

Figure 3. Varnished plywood channel with wooden cubes, n = 0.016.

V111. EXPERIMENTAL INVESTIGATION OF SPATIALLY VARIED FLOW

Description of Apparatus

In order to experimentally verify the accuracy of the nondimensional equation, an open channel with spatially varied flow was set up in the laboratory. The channel was ten feet long, six inches wide and had a bottom slope that could be varied from zero to two percent. The channel was made of varnished plywood, and the roughness of the channel was altered by tacking screen wire (1/4 inch mesh) to the channel and by nailing 3/4 inch wooden cubes to the channel. The results of an experimental investigation of Manning's roughness coefficient (section V11) showed that the varnished plywood channel had an approximate roughness coefficient of 0.008, the varnished plywood channel with the screen wire had an approximate roughness coefficient of 0.013, and the varnished plywood channel with the wooden cubes had an approximate roughness coefficient of 0.016.

A head box with a total volume of approximately 30 cubic feet was used to feed two side troughs from which water was added to the channel over two level side weirs. Aluminum vanes, perpendicular to the channel axis at two inch intervals, were attached to the side weirs in order to keep the inflow velocity perpendicular to the channel axis (figure 4). Therefore, the momentum added in the direction of flow in the channel should be negligible.

Manometer tubes, at one-foot intervals along the channel bottom, were used to measure the depth of flow. The manometer tubes were located 1.5 inches from the side of the channel so that the effect of the inflow impact on the depth readings would be reduced. A six inch ruler, attached at the channel outlet, was used to measure the depth at the downstream end of the channel.

Measurement of Discharge

The total discharge was obtained by measuring the pressure difference across an orifice plate which was located in the pipeline that fed the head box. A manometer (figure 5) was set up which measured the pressure difference, and the discharge was then obtained from a graph of "pressure difference versus discharge."

Experimental determination of the quantity of added flow along the channel axis was obtained at one-foot intervals along each weir. A container was held under the weir, and the time required to fill the container was recorded. Then, by weighing the water in the container, the volume of the collected water could be determined. Comparison of the theoretical uniform inflow values with the observed inflow values is shown in figure 6. The data obtained for these flow measurements are given in Table 1 , Appendix B.

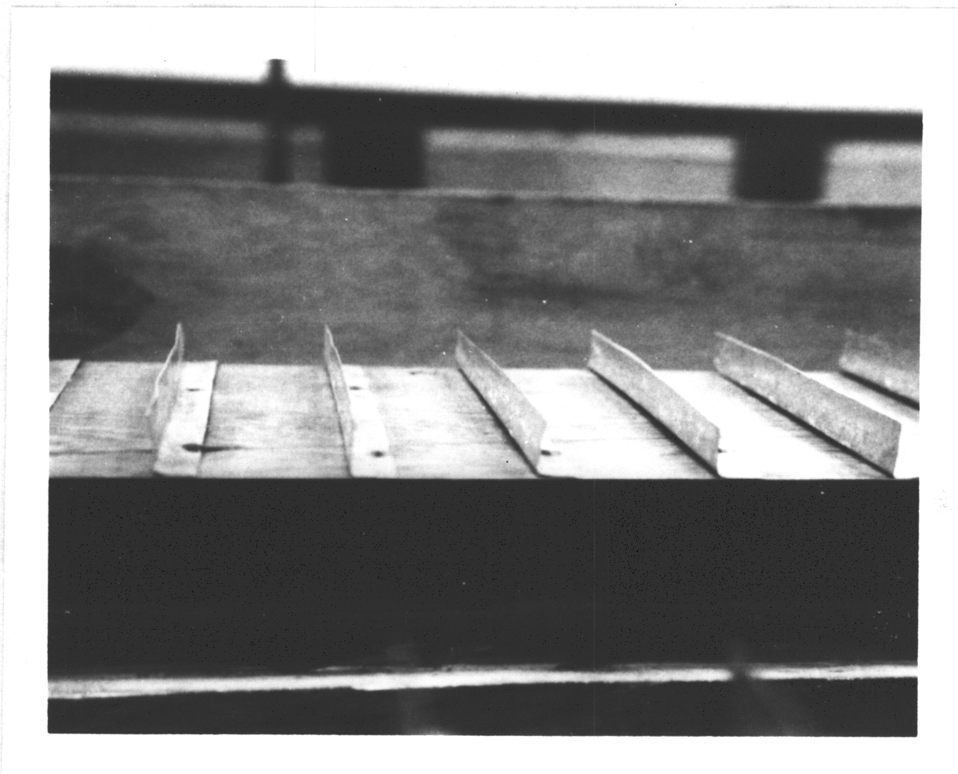

Figure 4. Aluminum vanes along the side weirs.

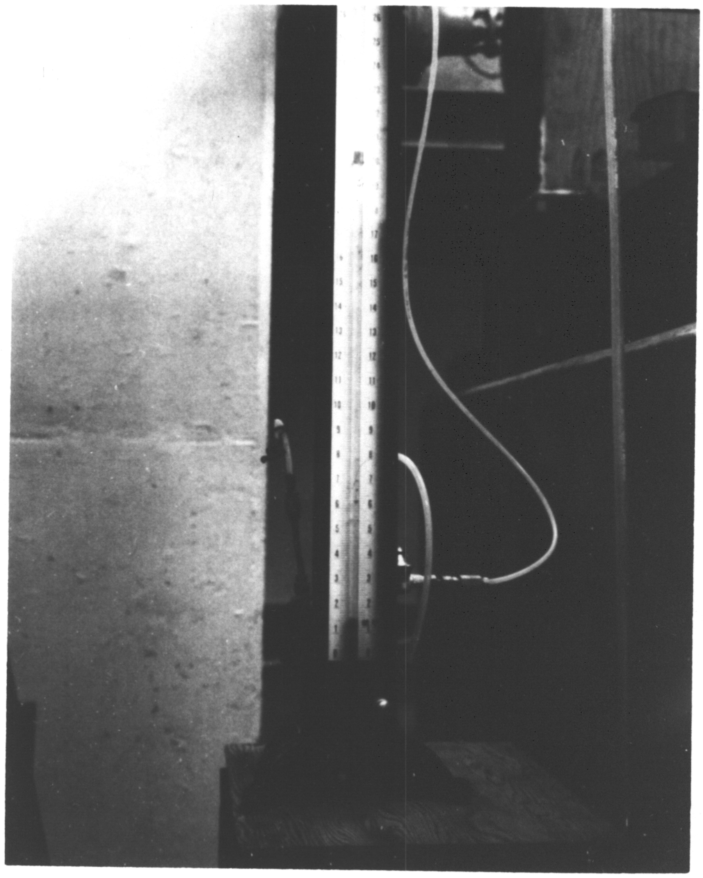

Figure 5. Manometer used to measure pressure difference across orifice plate.

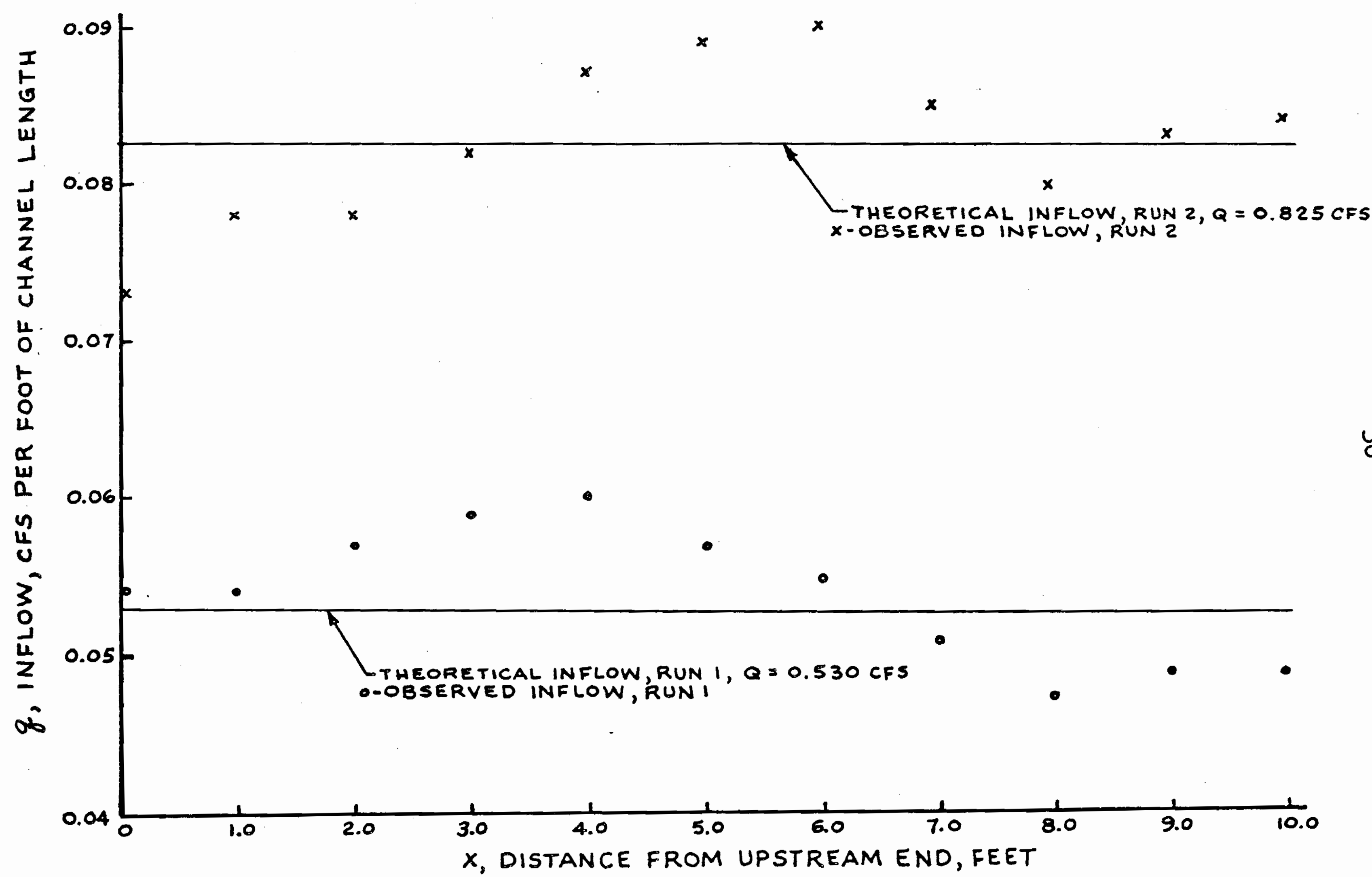

FIGURE 6. COMPARISON OF THEORETICAL AND OBSERVED VALUES OF INFLOW

IX. RESULTS

Uniform flow depth was measured for various rates of discharge in rectangular channels of varnished plywood, varnished plywood with screen wire, and varnished plywood with wooden cubes. From these measurements, Manning's roughness coefficients were calculated. Table 3, Appendix B shows the results of these measurements.

Water surface curves for the varnished plywood channel, the varnished plywood channel with screen wire, and the varnished plywood channel with wooden cubes were measured for two rates of discharge at sloped of zero, one and two percent. These curves are shown in figures 7, 8, 9, 10, 11, 12, 13, 14, and 15. Corresponding theoretical water surface curves computed from the nondimensional equation are also shown in these figures. The "observed" curves were plotted from the data in Table 2, Appendix B. A drawdown of the water surface was observed near the outlet of the channel. Henderson (10) shows the results of many investigations concerning drawdown curves near the outlet in open channels with continuous flow. Included in his discussion is a graph of y/y_o versus x/y_o for use near the outlet. Using this graph a theoretical drawdown in spatially varied flow was approximated (see figure 7).

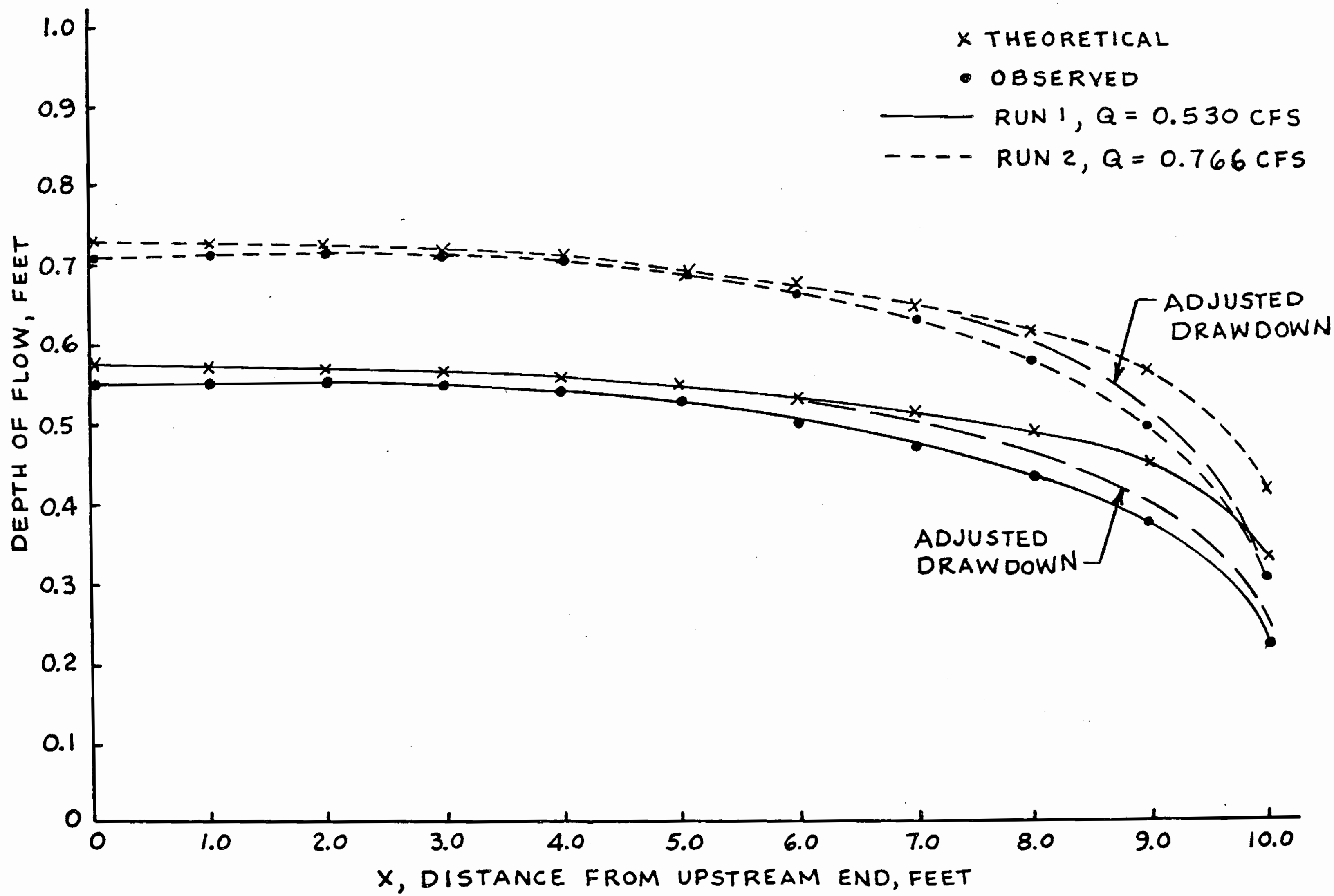

FIGURE 7. FLOW PROFILE FOR A LEVEL RECTANGULAR CHANNEL WITH A MANNING ROUGHNESS COEFFICIENT, n, OF 0.008.

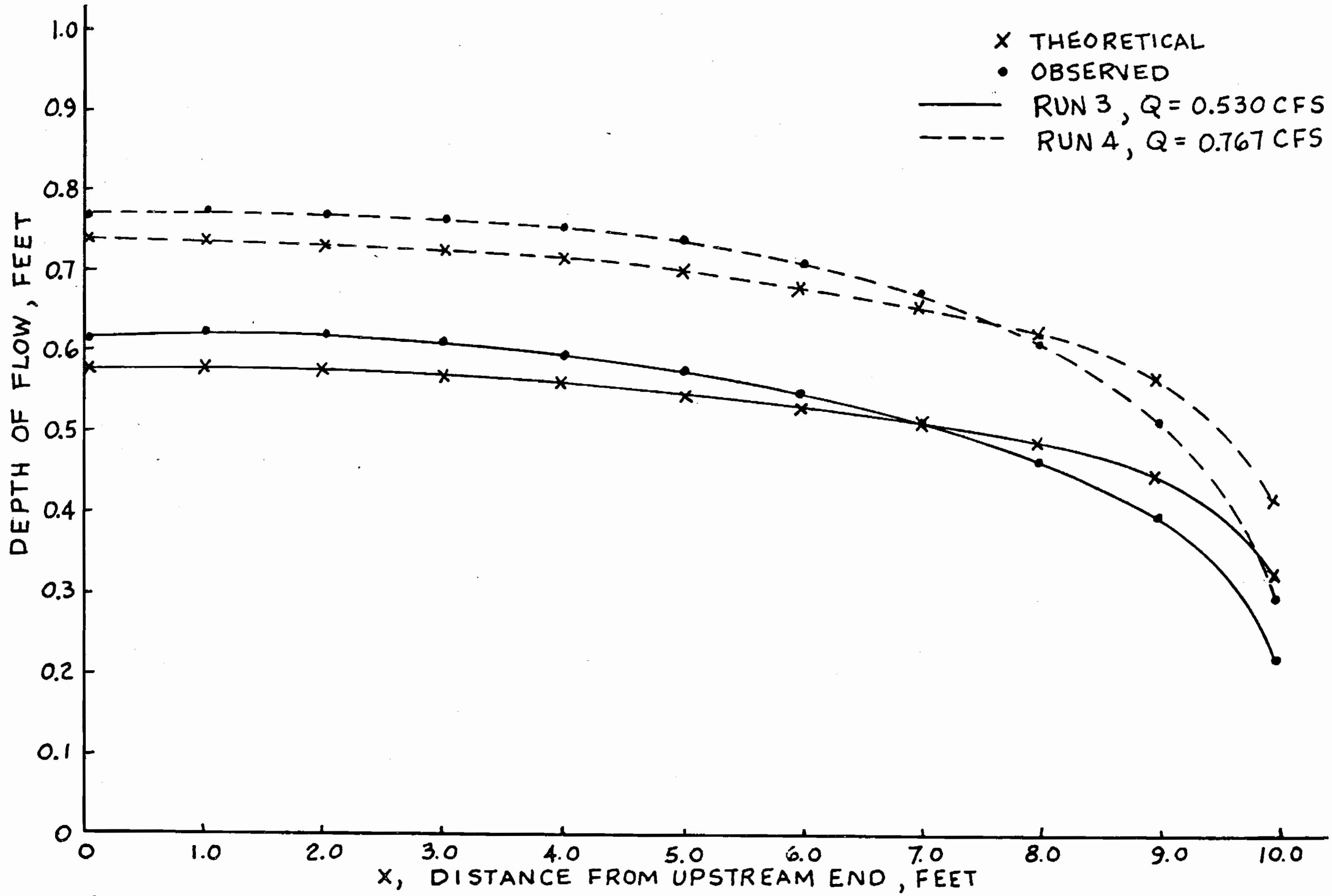

FIGURE 8. FLOW PROFILE FOR A LEVEL RECTANGULAR CHANNEL WITH A MANNING ROUGHNESS COEFFICIENT, n, OF 0.013.

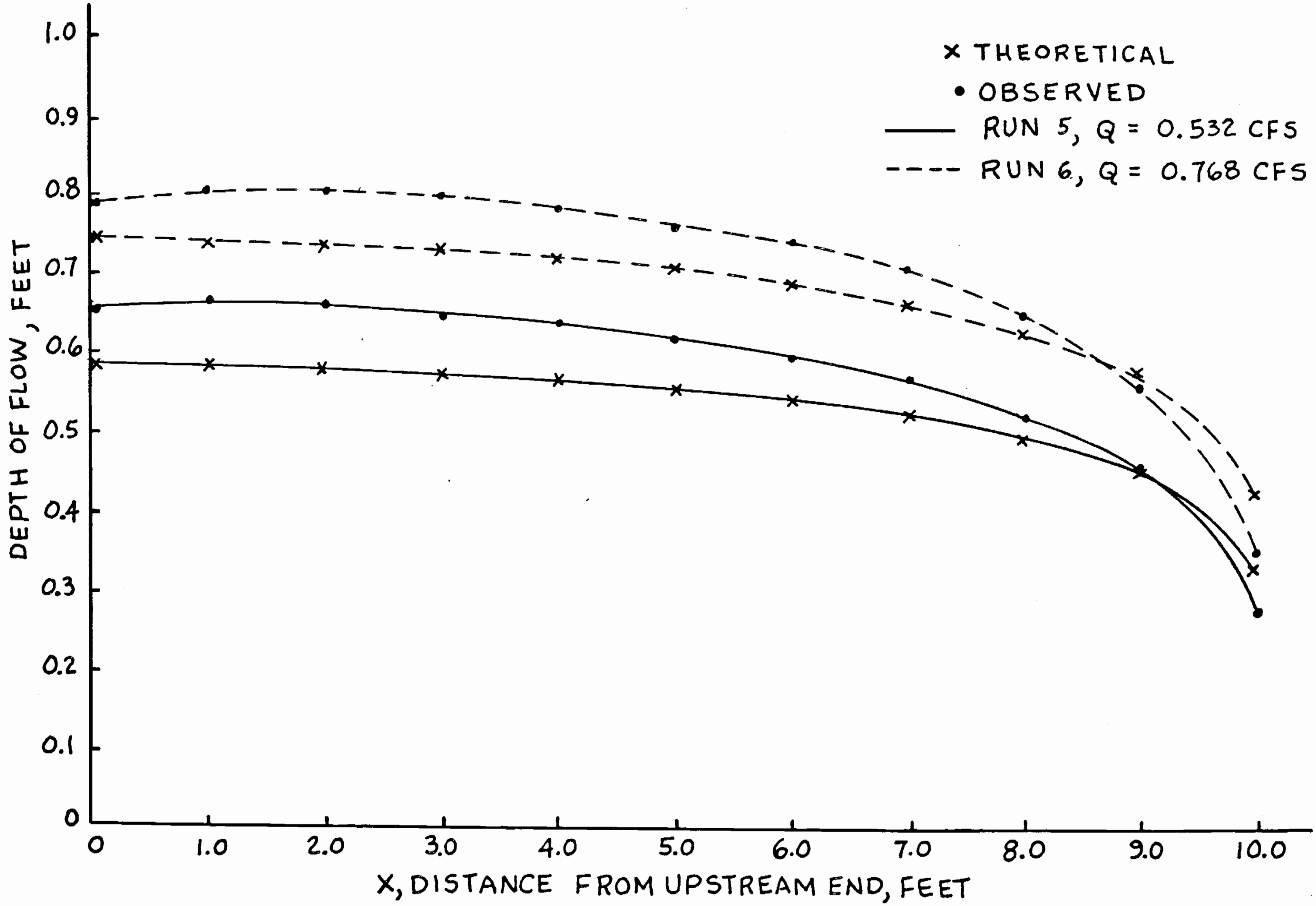

FIGURE 9. FLOW PROFILE FOR A LEVEL RECTANGULAR CHANNEL WITH A MANNING ROUGHNESS COEFFICIENT, n, OF 0.016.

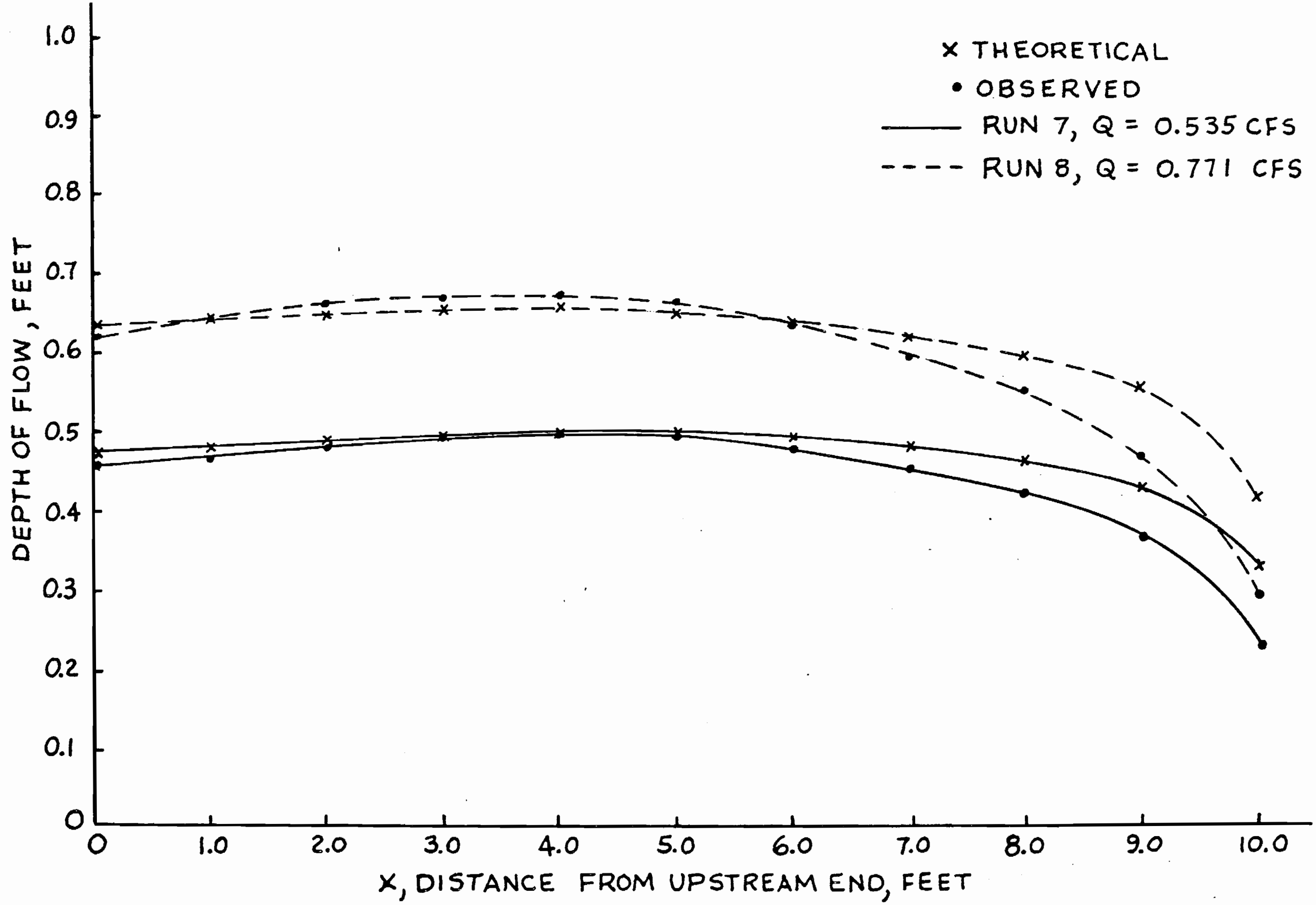

FIGURE 10. FLOW PROFILE FOR A RECTANGULAR CHANNEL WITH A SLOPE OF 0.01 AND A MANNING ROUGHNESS COEFFICIENT, n, OF 0.008.

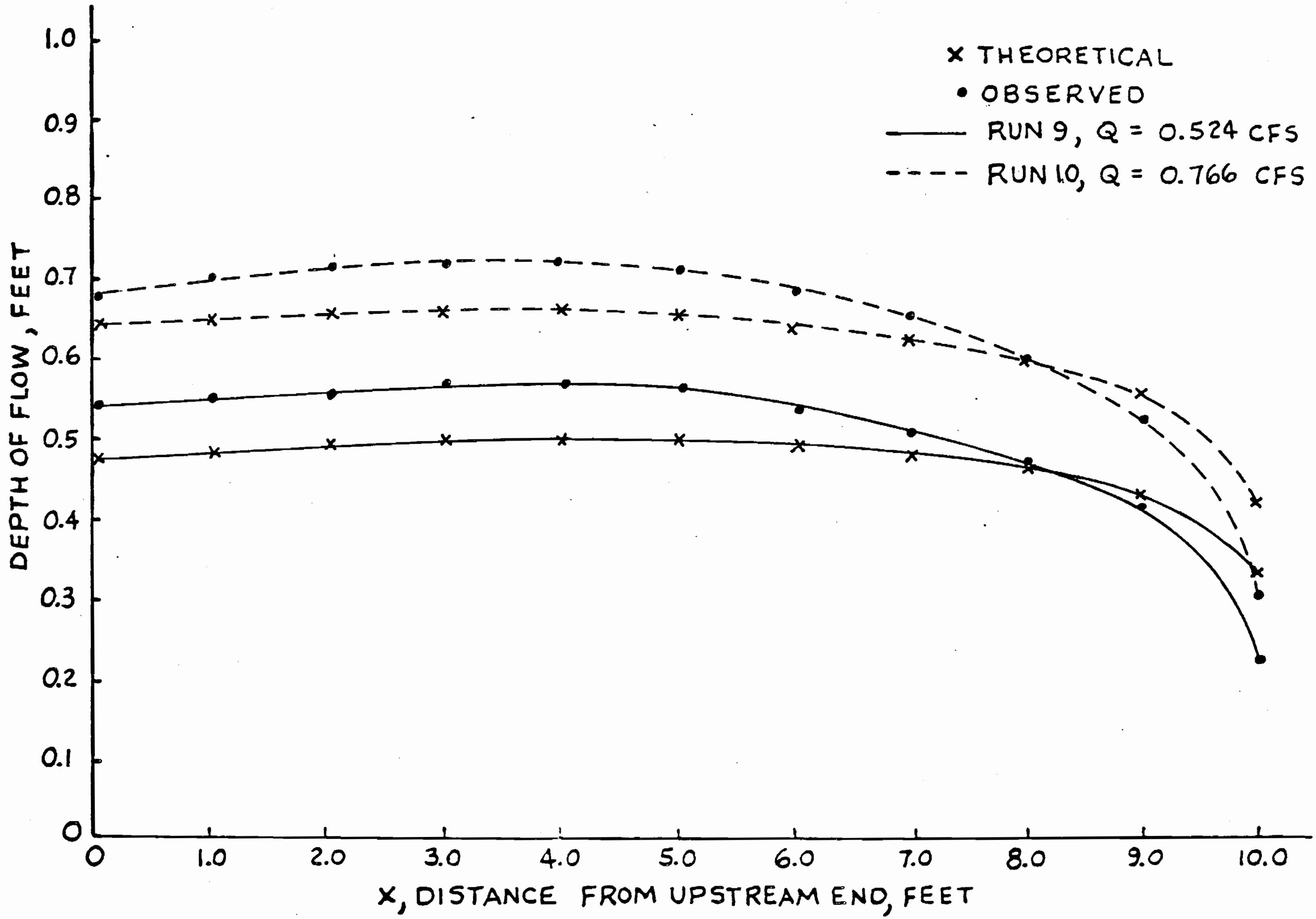

FIGURE 11. FLOW PROFILE FOR A RECTANGULAR CHANNEL WITH A SLOPE OF 0.01 AND A MANNING ROUGHNESS COEFFICIENT, n, OF 0.013.

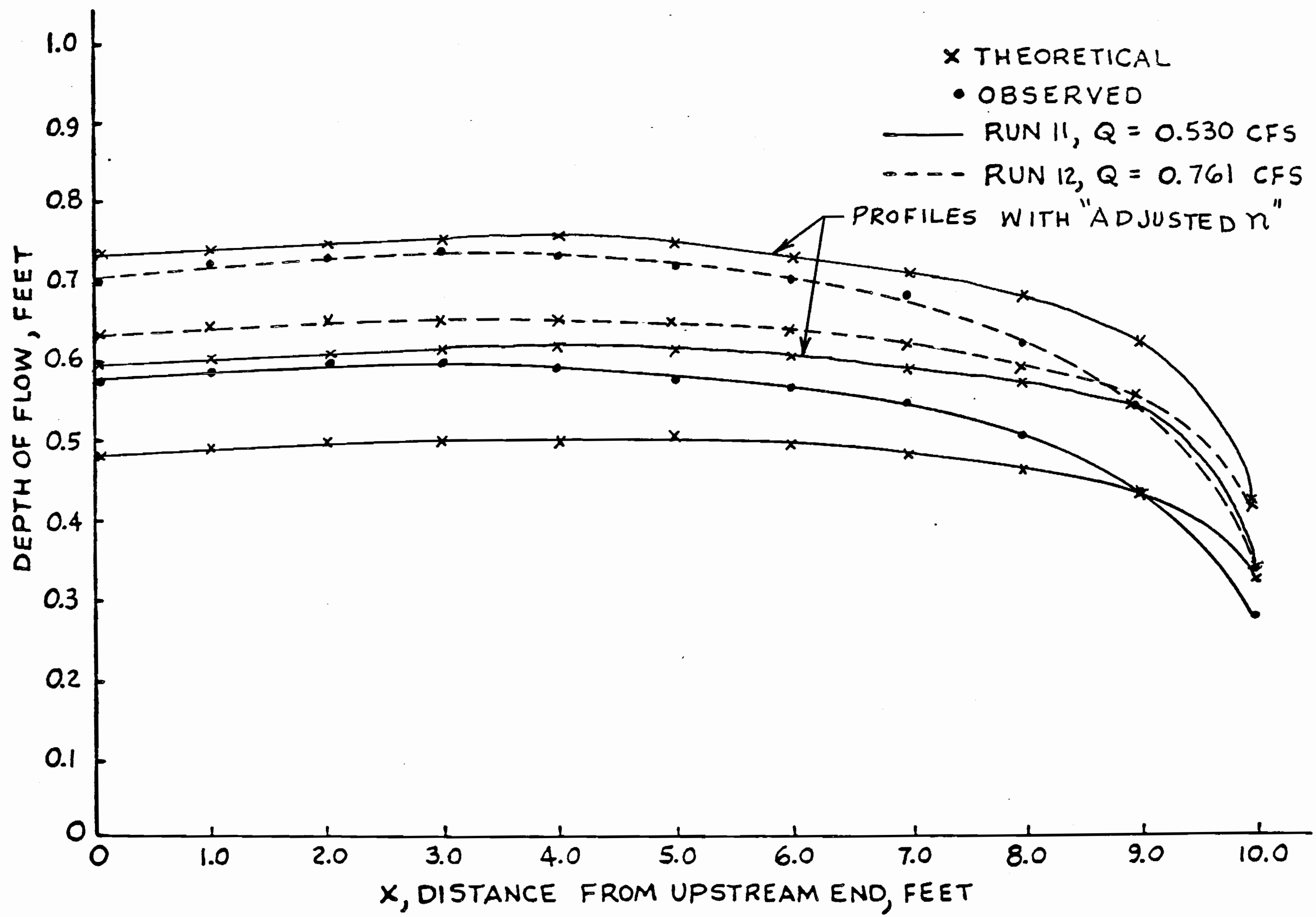

FIGURE 12. FLOW PROFILE FOR A RECTANGULAR CHANNEL WITH A SLOPE OF 0.01 AND A MANNING ROUGHNESS COEFFICIENT, n, OF 0.016.

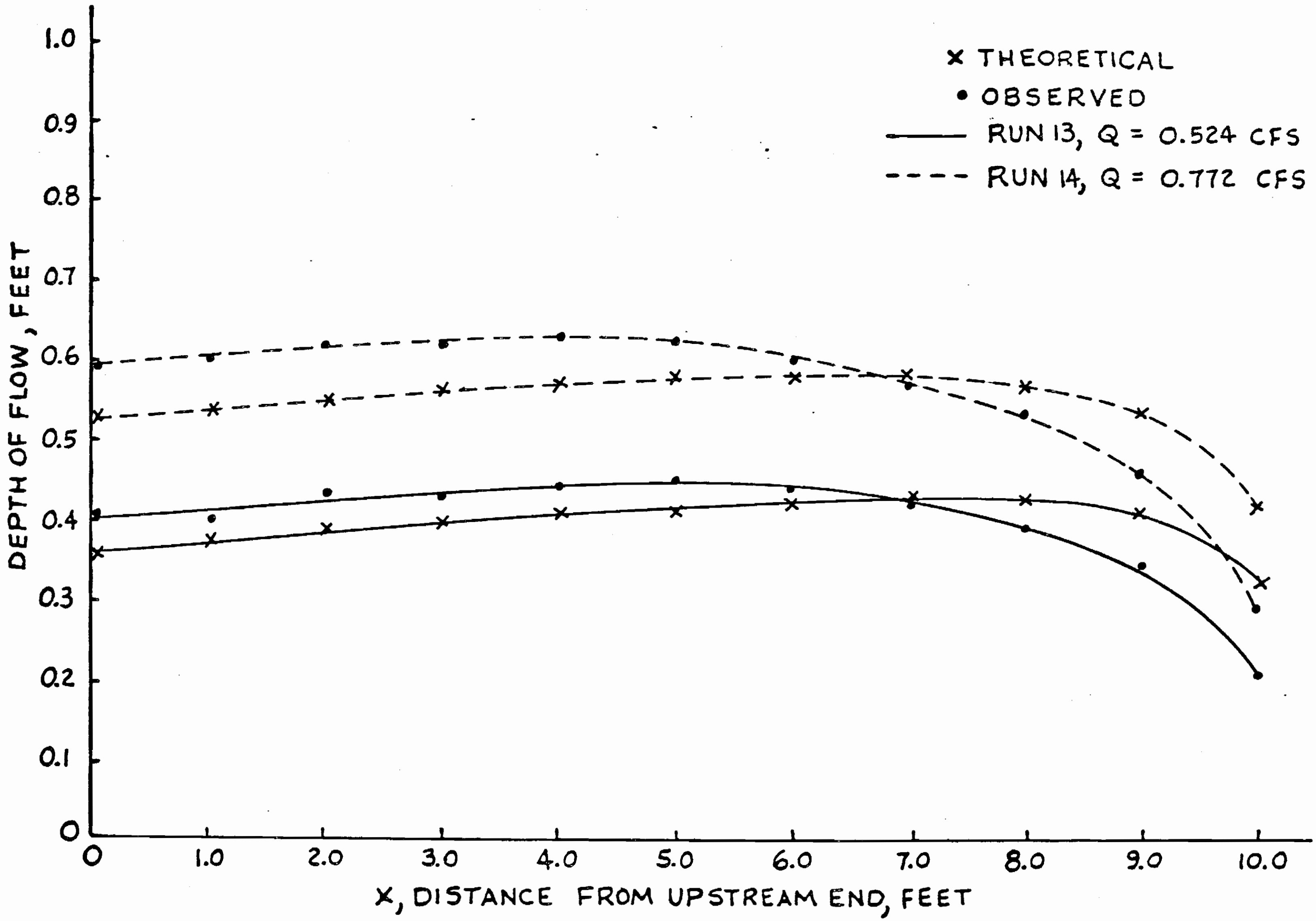

FIGURE 13. FLOW PROFILE FOR A RECTANGULAR CHANNEL WITH A SLOPE OF 0.02 AND A MANNING ROUGHNESS COEFFICIENT, n, OF 0.008.

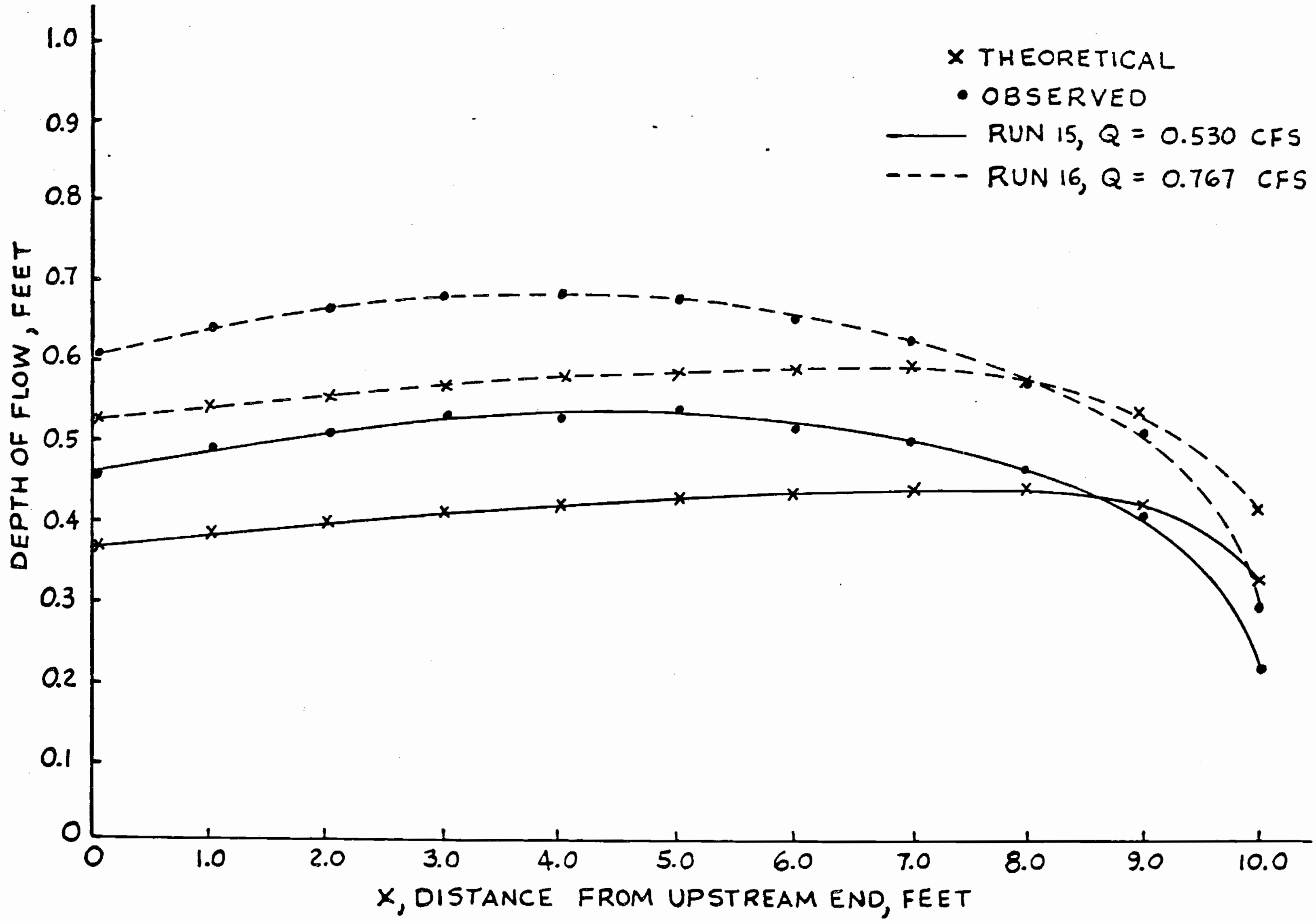

FIGURE 14. FLOW PROFILE FOR A RECTANGULAR CHANNEL WITH A SLOPE OF 0.02 AND A MANNING ROUGHNESS COEFFICIENT, n, OF 0.013.

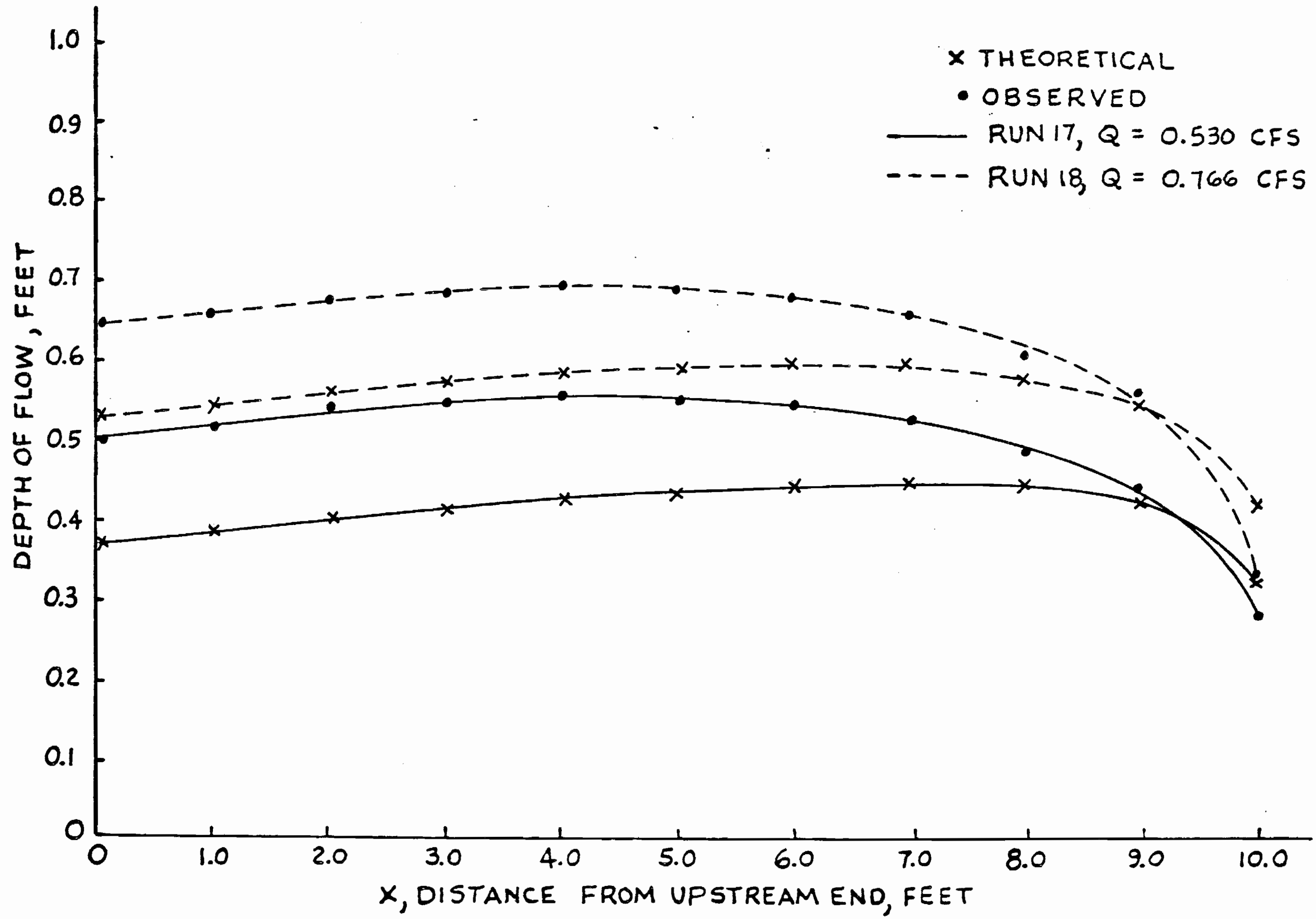

FIGURE 15. FLOW PROFILE FOR A RECTANGULAR CHANNEL WITH A SLOPE OF 0.02 AND A MANNING ROUGHNESS COEFFICIENT, n, OF 0.016.

X. DISCUSSION OF RESULTS

Using two rates of discharge, flow profiles were experimentally obtained for spatially varied flow in rectangular channels with Manning roughness coefficients of 0.008, 0.013, and 0.016 and with slopes of zero, one, and two percent. Data collected for these profiles are given in Table 2, Appendix B. Theoretical flow profiles for the same values of slope, roughness, and discharge were obtained by solving the nondimensional equation for spatially varied flow on an IBM 7040 computer. Figures 7 through 15 show comparisons between the theoretical and observed profiles.

These figures indicate that the differences between the theoretical and observed flow profiles increased as the slope and roughness of the channel increased. Most of these differences can probably be attributed to the use of Manning's equation in computing the friction factor. Manning's equation describes the effect of friction when uniform flow exists in channels with small slopes. Since there is no known method for describing the effects of friction in channels with spatially varied flow, errors are introduced in the analysis.

Some error is probably due to the difference between theoretical uniform inflow and actual inflow. Errors from this source, and from the assumption that there is no inflow velocity component in the direction of flow are believed to be negligible.

Solutions obtained with the digital computer indicate that the nondimensional flow profiles vary slightly over a wide range of discharge when the roughness and slope of the channel are constant (see Table 4, Appendix B). Therefore, the nondimensional equation can be used for obtaining accurate flow profiles if an expression can be found for describing the effects of friction in spatially varied flow. Nondimensional flow profiles for rectangular channels with slopes of zero, one, and two percent are shown in figures 16, 17, and 18. An example problem using these nondimensional profiles is given in Appendix A.

The nondimensional equation was solved with various values of Manning's n until agreement was obtained between the theoretical and observed profiles. Using this procedure, adjustments were made to the experimentally determined values of n (Figure 19). By adjusting the values of Manning's n for various channels, the nondimensional equation should be highly accurate for determining water surface profiles in rectangular channels.

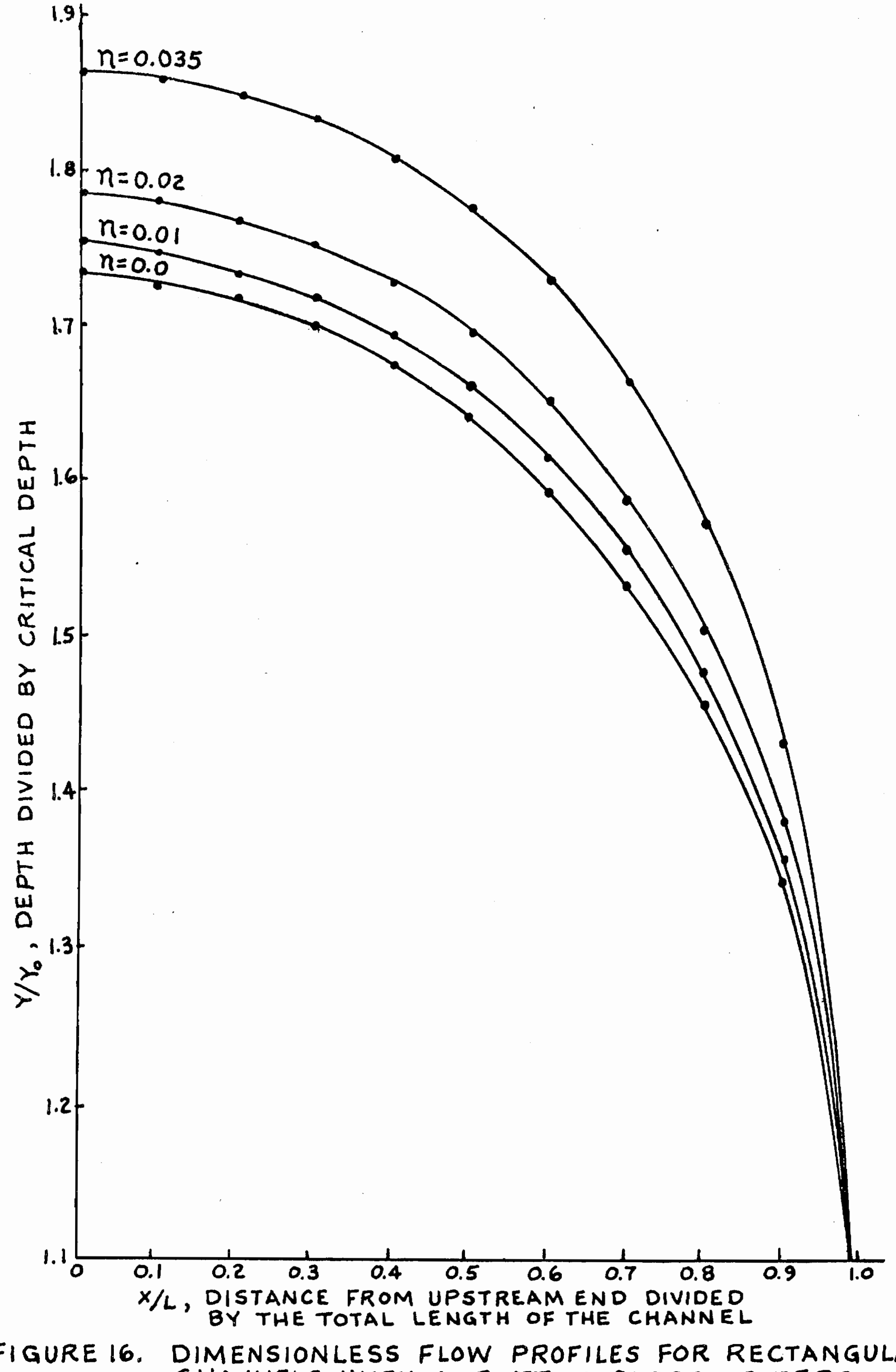

FIGURE 16. DIMENSIONLESS FLOW PROFILES FOR RECTANGULAR CHANNELS WITH A BOTTOM SLOPE OF ZERO.

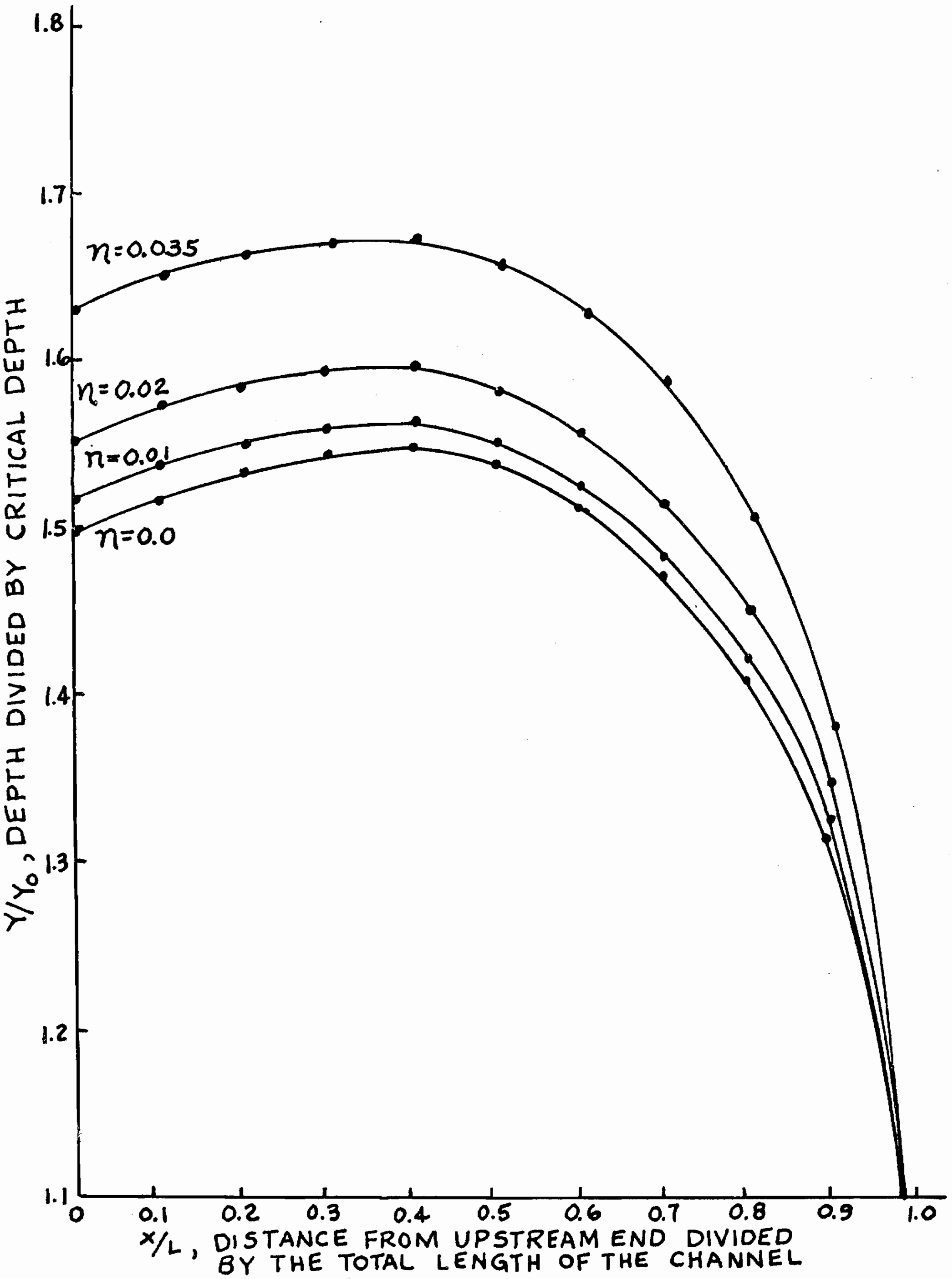

FIGURE 17. DIMENSIONLESS FLOW PROFILES FOR RECTANGULAR CHANNELS WITH A BOTTOM SLOPE OF 1.0%.

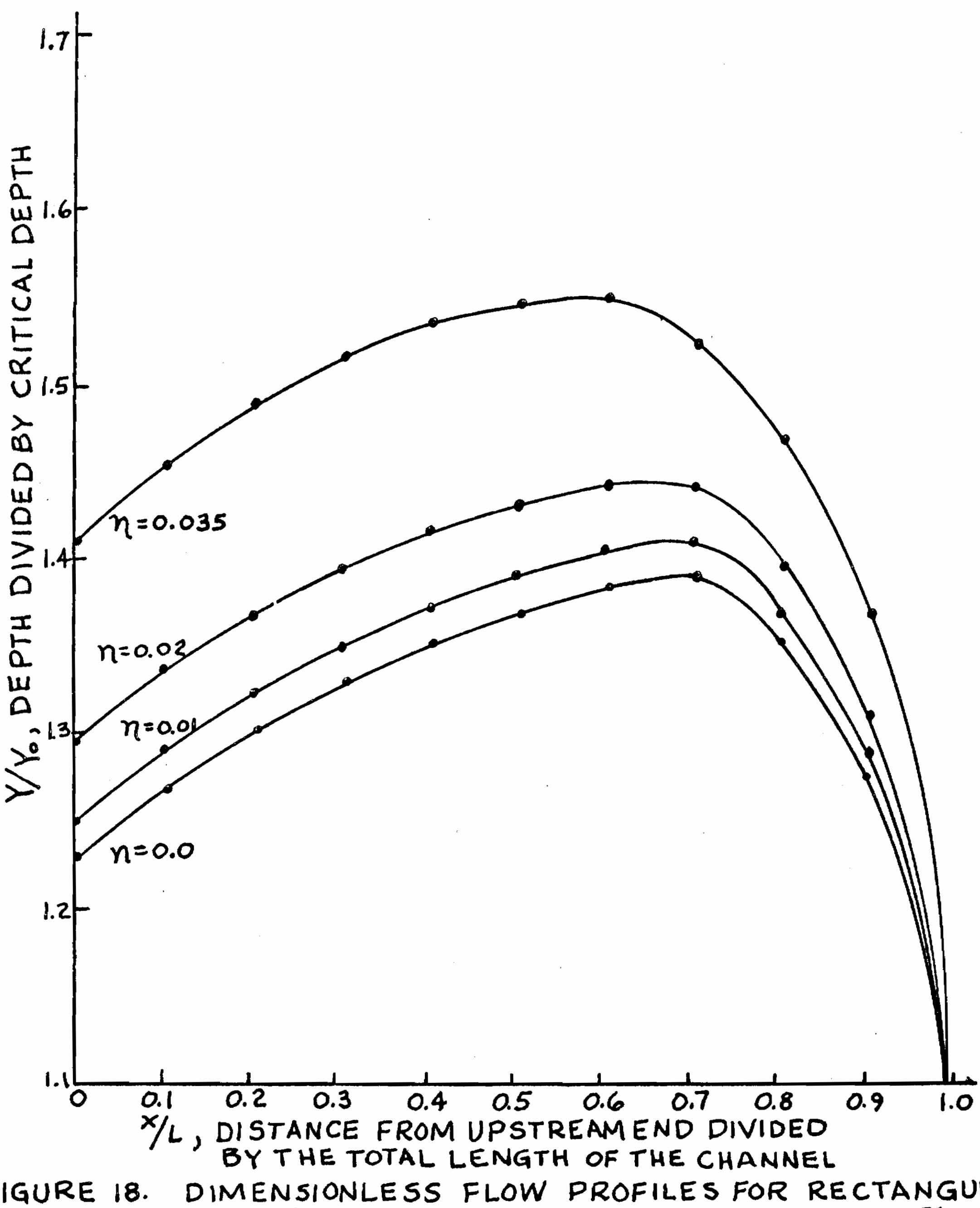

FIGURE 18. DIMENSIONLESS FLOW PROFILES FOR RECTANGULAR CHANNELS WITH A BOTTOM SLOPE OF 2.0%.

Figure 19. Table of adjusted roughness values.

	Manning Roughness Coefficient	
	Experimental	Adjusted
Slope = 0%		
Varnished plywood channel.	n = 0.008	n = 0.008
Varnished plywood channel with screen wire.	n = 0.013	n = 0.035
Varnished plywood channel with wooden cubes.	n = 0.016	n = 0.050
Slope = 1%		
Varnished plywood channel.	n = 0.008	n = 0.010
Varnished plywood channel with screen wire.	n = 0.013	n = 0.040
Varnished plywood channel with wooden cubes.	n = 0.016	n = 0.055
Slope = 2%		
Varnished plywood channel.	n = 0.008	n = 0.025
Varnished plywood channel with screen wire.	n = 0.013	n = 0.045
Varnished plywood channel with wooden cubes.	n = 0.016	n = 0.055

In order to illustrate the use of the "adjusted n" values, flow profiles are included in figure 12.

XI. SUMMARY AND CONCLUSIONS

A nondimensional form of the basic differential equation for spatially varied flow with increasing discharge was developed in section VI. The main purpose of this thesis is the application of this nondimensional equation to rectangular channels of various roughness values.

A rectangular channel with continuous flow was constructed in order to establish uniform flow. The channel roughness was altered by placing screen wire and wooden cubes in the channel. Manning roughness coefficients were determined from the observed values for uniform depth.

The law of conservation of linear momentum was used to develop a differential equation for spatially varied flow with increasing discharge. By defining certain dimensionless parameters, this equation was altered to a dimensionless form. An IBM 7040 computer was used to solve this nondimensional equation for various conditions of slope, roughness, and discharge. When the channel slope and roughness were held constant, the theoretical profiles varied slightly over a wide range of discharge.

Flow profiles for spatially varied flow in rectangular channels were observed in the laboratory. The rectangular channel under investigation was ten feet long, six inches wide, and had a variable bottom slope. By placing screen wire and wooden cubes in the channel, the roughness of the channel was altered. Water surface profiles were measured for each of three different roughness values at two rates of discharge with slopes of zero, one, and two percent.

By comparing the observed flow profiles with the theoretical profiles, the following conclusions can be drawn:

1. When the slope and roughness of the channel are known, the dimensionless flow profile for spatially varied flow in rectangular channels is relatively constant for a wide range of discharge.
2. A problem exists in determining an appropriate roughness coefficient for spatially varied flow. It appears that the friction factors in channels with spatially varied flow are quite different from the friction factors in similar channels with uniform flow. It is also obvious that the losses due to turbulence in spatially varied flow is a significant factor which cannot be neglected.

3. The observed water surface profiles indicate that a drawdown of the flow exists near the channel outlet. Therefore, a more accurate theoretical profile is obtained by adjusting the curve near the outlet as shown in figure 7.

Although this study was mainly concerned with spatially varied flow in rectangular channels with uniform inflow, a computer program was also written to determine the nondimensional flow profiles when the inflow varied in a triangular shape. Solutions to this program indicate that the nondimensional water surface profile is dependent on the inflow pattern, but stays relatively constant over a wide range of discharge (see Table 5, Appendix B).

XII. SUGGESTIONS FOR FUTHER STUDY

It is suggested that a study be made concerning the frictional forces in spatially varied flow. Comparison of experimentally determined Manning roughness coefficients with adjusted coefficients, such as described in section X, may lead to an accurate method for determining friction factors for spatially varied flow.

A study should also be undertaken in relation to the drawdown of the water surface near the channel outlet so that the solution of the nondimensional equation can be altered to obtain highly accurate water surface profiles.

It is also suggested that a digital computer program be written to include a general expression for describing a variable incremental inflow.

XIII. ACKNOWLEDGEMENTS

The author would like to express his appreciation to Dr. James M. Wiggert for his leadership and guidance during the investigation and writing of this thesis.

Appreciation is also expressed to all my professors and fellow students for their help and friendship during my tenure at Virginia Polytechnic Institute.

Special thanks is extended to my wife, Ann, for her encouragement and typing ability which made this thesis possible.

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XV. VITA

The author was born in Newport News, Virginia on June 2, 1942. After graduating from Newport News High School in June, 1960, he attended the Virginia Polytechnic Institute Extension at the Norfolk College of William and Mary for two years. In September of 1962, he transferred to Virginia Polytechnic Institute for one year. The following year he worked for the Newport News Shipbuilding and Dry Dock Company. He returned to Virginia Polytechnic Institute in June of 1964 and received a Bachelor of Science degree in Civil Engineering in June, 1965.

He married Ann Shirley Livesay on December 15, 1962, and they have two children, Nancy Dianne and Kathy Lynn. The family is now residing in Blacksburg, Virginia, while he is fulfilling the requirements for the Master of Science degree in Civil Engineering at Virginia Polytechnic Institute.

Robert Wayne Johnson

XVl. <u>APPENDIX</u> <u>A</u>:

Example Problem

Determine the flow profile for a rectangular channel that carries a total discharge of 100 cubic feet per second. The channel is made of corrugated metal with a roughness coefficient of 0.020. The channel is 80.0 feet long, 3.0 feet wide, and has a bottom slope of 1%.

SOLUTION:

$$\text{Critical depth} = \sqrt[3]{q^2/g} = \sqrt[3]{(100/3)^2\,/32.2} = 3.25\text{ ft.}$$

From figure 17 (section X)

x	x/L	y/y_o	y
0	0.000	1.553	5.05
10	0.125	1.575	5.12
20	0.250	1.589	5.16
30	0.375	1.595	5.18
40	0.500	1.580	5.14
50	0.625	1.555	5.05
60	0.750	1.483	4.82
70	0.875	1.372	4.46
80	1.000	1.000	3.25

XVll. APPENDIX B:

Data

TABLE 1. Data For Comparison of Actual Inflow with Theoretical Inflow

Measuring Container Width = 0.539 feet

Discharge = Weight/(time) w (.539), cubic feet per second

w = unit weight of water, pounds per cubic feet

X = distance from upstream end, feet

W = weight of inflow, pounds

T = Time, seconds

I = inflow, cfs/ft.

Q = total inflow, cfs/ft.

Run No. 1	Total Discharge = 0.530 cfs									Weir No. 1
X	0	1	2	3	4	5	6	7	8	9	10
W	3.30	3.50	3.69	3.94	4.87	4.19	3.50	3.63	3.35	3.60	3.50
T	3.80	4.00	3.75	3.85	4.50	4.25	3.75	4.00	3.85	4.15	3.95
I	.026	.026	.029	.030	.032	.029	.028	.027	.026	.026	.026
											Weir No. 2
X	0	1	2	3	4	5	6	7	8	9	10
W	3.85	3.80	3.44	3.90	3.90	3.69	3.70	3.50	2.81	3.00	3.20
T	4.05	4.00	3.60	3.95	4.15	3.90	4.10	4.40	3.80	3.90	4.20
I	.028	.028	.028	.029	.028	.028	.027	.024	.022	.023	.023
Q	.054	.054	.057	.059	.060	.057	.055	.051	.048	.049	.049

Run No. 2	Total Discharge = .825 cfs								Weir No. 1	
X	0	1	2	3	4	5	6	7	8	9	10
W	3.40	2.85	3.20	3.35	3.90	4.35	3.50	3.65	3.80	4.20	3.90
T	2.80	2.10	2.50	2.50	2.70	2.90	2.30	2.45	2.75	2.90	2.70
I	.036	.040	.038	.040	.043	.045	.045	.044	.041	.043	.043

Weir No. 2

X	0	1	2	3	4	5	6	7	8	9	10
W	4.05	3.90	4.50	4.15	4.40	4.80	4.10	3.97	4.20	4.08	3.95
T	3.25	3.05	3.35	2.95	3.00	2.55	2.70	2.90	3.20	3.05	2.85
I	.037	.038	.040	.042	.044	.044	.045	.041	.039	.040	.041
Q	.073	.078	.078	.082	.087	.089	.090	.085	.080	.083	.084

TABLE 2.

Experimental Flow Profile Data for Rectangular Channels with Spatially Varied Flow

Depth in Thousandth of a foot

Run No. 1 Total Discharge = 0.530 cfs

Slope = 0.0% n = .008

x	0	1	2	3	4	5	6	7	8	9	10
1	550	550	550	550	538	529	492	467	429	379	221
2	546	546	554	546	542	538	496	463	433	375	221
3	554	546	550	542	538	530	496	467	429	375	225
4	542	550	554	550	550	521	492	463	433	379	221
5	550	554	554	546	538	529	496	467	433	375	217
6	542	550	550	563	546	521	500	463	429	379	221
7	554	550	554	558	534	525	504	467	425	375	217
8	558	550	550	546	530	525	496	463	429	371	221
9	550	550	546	542	542	529	496	467	429	371	225
10	563	563	554	542	530	521	496	459	425	375	221
Averages	551	551	552	548	539	527	496	465	429	375	221

Run No. 2 Total Discharge = 0.766 cfs

Slope = 0.0% n = .008

x	0	1	2	3	4	5	6	7	8	9	10
1	721	725	721	704	688	671	646	604	554	475	305
2	709	713	713	708	700	692	662	629	579	496	308
3	709	713	716	704	704	687	663	633	579	492	304
4	705	709	716	708	708	683	658	629	583	496	308
5	709	713	721	712	704	687	658	629	579	496	300
6	705	709	713	704	700	692	662	629	583	496	304
7	701	713	713	704	700	692	667	633	583	492	305
8	709	713	721	713	704	687	658	629	583	492	305
9	713	713	721	708	708	683	658	629	579	496	300
10	705	713	721	704	704	692	654	629	579	496	305
Averages	709	713	718	707	702	687	659	627	578	493	304

Run No. 3 Total Discharge = .530 cfs

Slope = 0% n = .013

x	0	1	2	3	4	5	6	7	8	9	10
1	617	621	617	609	596	579	542	512	467	396	221
2	608	625	617	613	592	575	546	508	467	400	225
3	612	625	617	613	592	579	542	513	467	396	229
4	616	625	617	609	592	575	546	513	467	400	225
5	617	621	621	609	592	575	546	512	467	400	221
6	608	621	621	609	592	575	542	508	467	396	221
7	612	621	617	609	592	579	546	513	467	396	221
8	617	621	617	609	592	575	542	508	467	400	225
9	608	625	617	609	592	571	542	513	467	400	225
10	617	625	621	613	596	579	546	513	467	400	221
Averages	613	623	618	610	593	576	544	511	467	398	223

Run No. 4 Total Discharge = .767 cfs

Slope = 0% n = .013

x	0	1	2	3	4	5	6	7	8	9	10
1	758	767	771	758	754	738	713	671	612	517	296
2	763	771	771	763	754	738	713	675	613	513	300
3	767	767	767	758	750	738	712	675	613	517	296
4	758	771	767	763	746	742	717	671	613	517	296
5	758	771	763	767	750	738	709	671	612	517	292
6	758	771	767	763	750	738	713	671	608	517	296
7	758	771	767	767	754	742	713	671	612	517	296
8	754	771	767	767	750	738	709	671	613	521	296
9	763	771	767	763	754	738	713	675	613	517	292
10	775	783	775	767	746	729	692	667	600	508	300
Averages	761	771	768	764	751	738	710	672	611	516	296

Run No. 5 Total Discharge = .532 cfs

Slope = 0% n = .016

x	0	1	2	3	4	5	6	7	8	9	10
1	650	663	658	646	638	608	588	562	517	450	271
2	650	662	658	646	637	613	588	566	517	454	271
3	650	662	658	646	638	613	592	562	517	450	271
4	650	663	654	646	634	612	588	566	517	454	267
5	650	663	658	646	637	613	592	562	521	454	271
6	650	662	658	646	638	613	588	562	517	454	275
7	646	663	654	646	638	613	588	562	517	454	275
8	650	662	658	650	634	617	588	562	517	450	271
9	650	658	658	646	634	612	592	566	517	450	267
10	650	662	654	642	638	613	592	566	521	454	271
Averages	650	662	657	646	637	613	590	564	518	452	271

Run No. 6 Total Discharge .768 cfs

Slope = 0% n = .016

x	0	1	2	3	4	5	6	7	8	9	10
1	788	800	800	792	779	754	734	704	646	550	346
2	792	804	800	788	779	754	738	700	646	554	350
3	788	804	800	796	779	763	734	704	646	550	342
4	788	804	800	792	779	754	733	704	646	554	346
5	784	800	800	792	783	759	734	700	646	550	346
6	788	800	800	792	779	759	734	700	646	550	350
7	784	800	800	796	775	759	738	700	646	554	346
8	798	804	800	788	779	754	729	704	646	550	342
9	792	804	800	792	779	754	734	704	646	550	346
10	788	800	800	796	779	759	738	704	646	554	346
Averages	788	802	800	792	779	757	735	702	646	552	346

Run No. 7 Total Discharge = .535 cfs

Slope = 1% n = .008

x	0	1	2	3	4	5	6	7	8	9	10
1	471	500	500	500	500	484	492	458	429	375	229
2	463	462	479	496	488	496	479	450	421	359	233
3	450	462	483	484	496	492	475	454	421	367	225
4	454	466	475	492	500	496	475	450	425	363	229
5	458	462	479	496	492	488	471	454	416	367	229
6	467	471	488	500	500	492	479	454	421	371	225
7	454	471	479	492	496	496	479	450	425	367	233
8	458	466	475	488	492	488	475	450	421	367	229
9	467	466	471	492	500	492	479	450	421	367	229
10	458	466	483	492	504	492	479	450	421	371	229
Averages	460	469	481	493	497	492	478	452	422	367	229

Run No. 8 Total Discharge = .771 cfs

Slope = 1% n = .008

x	0	1	2	3	4	5	6	7	8	9	10
1	613	634	658	675	679	671	634	591	550	475	292
2	621	642	662	671	675	662	633	587	550	467	292
3	617	646	658	667	671	667	629	592	546	471	292
4	621	646	662	662	675	662	633	591	550	467	296
5	625	642	667	658	671	667	629	596	554	471	292
6	621	646	662	662	671	667	625	592	550	467	288
7	625	646	662	667	667	662	629	592	550	467	296
8	625	646	662	671	671	662	634	596	550	471	292
9	621	646	658	667	675	667	637	591	554	471	292
10	625	646	658	662	667	667	625	592	554	475	292
Averages	621	644	662	666	672	665	631	592	551	470	292

Run No. 9 Total Discharge = .524 cfs

Slope = 1% n = .013

x	0	1	2	3	4	5	6	7	8	9	10
1	542	546	563	571	567	558	525	500	462	408	213
2	538	546	546	571	563	558	529	508	466	412	217
3	538	542	550	567	567	563	525	504	462	409	213
4	534	546	554	567	563	563	525	504	462	408	213
5	542	542	558	571	567	558	529	508	466	412	209
6	538	542	550	571	558	558	533	504	462	408	213
7	534	546	546	563	562	558	529	504	462	412	217
8	538	538	554	567	567	558	529	500	466	417	209
9	534	542	550	567	563	563	529	504	462	412	213
10	538	542	550	567	558	563	533	500	466	412	213
Averages	538	543	552	567	564	560	528	504	464	411	213

Run No. 10 Total Discharge = .766 cfs

Slope = 1% n = .013

x	0	1	2	3	4	5	6	7	8	9	10
1	692	700	704	717	704	704	671	642	588	517	296
2	675	696	704	717	725	708	684	650	600	521	300
3	671	692	704	721	721	708	688	654	596	521	300
4	675	692	704	725	721	708	688	650	600	517	296
5	679	696	704	717	717	712	684	650	600	521	296
6	675	696	708	721	725	717	688	654	596	521	300
7	675	692	704	721	721	708	684	650	600	521	296
8	675	696	704	721	721	708	684	654	592	521	296
9	671	692	708	725	725	712	688	650	596	525	296
10	675	696	704	725	721	717	684	654	600	521	296
Averages	676	695	705	721	720	717	684	651	597	521	297

Run No. 11 Total Discharge = .530

Slope = 1% n = .016

x	0	1	2	3	4	5	6	7	8	9	10
1	567	584	600	600	592	575	571	537	504	450	275
2	575	584	604	596	592	579	563	541	500	446	271
3	584	584	596	592	592	579	571	546	504	446	275
4	580	584	596	600	592	579	571	546	504	446	279
5	571	588	596	596	592	575	567	542	504	446	275
6	575	584	596	600	596	575	567	542	508	446	275
7	571	584	600	600	592	579	563	546	504	442	275
8	571	580	596	596	592	579	571	541	504	446	275
9	567	584	592	592	592	579	571	541	504	442	275
10	571	580	600	604	592	575	567	542	500	446	275
Averages	573	584	598	598	592	577	568	546	504	446	275

Run No. 12 Total Discharge = .761 cfs

Slope = 1% n = .016

x	0	1	2	3	4	5	6	7	8	9	10
1	700	725	734	742	734	725	704	679	625	550	338
2	704	725	734	738	738	721	704	683	621	546	342
3	708	725	730	738	734	725	708	683	625	546	338
4	700	725	734	738	734	725	704	683	621	550	334
5	700	725	734	742	730	717	704	683	621	546	338
6	700	725	730	742	738	721	708	683	625	550	338
7	700	725	734	738	734	725	704	683	625	546	334
8	700	725	730	742	738	721	700	687	625	546	334
9	700	725	730	738	734	725	700	683	625	550	338
10	700	725	734	742	734	721	704	679	621	546	338
Averages	701	725	732	740	735	723	704	683	623	548	337

Run No. 13 Total Discharge = .524 cfs

Slope = 2% n = .008

x	0	1	2	3	4	5	6	7	8	9	10
1	400	396	434	425	442	446	433	421	392	358	212
2	408	396	425	434	446	454	441	421	396	358	208
3	408	404	437	437	446	458	442	425	400	350	212
4	420	408	446	438	450	454	450	429	404	350	208
5	404	396	429	434	446	446	433	425	392	354	208
6	402	402	442	428	442	454	442	421	400	350	208
7	410	404	437	432	446	458	433	425	396	350	212
8	408	396	425	437	450	446	442	422	392	350	208
9	406	408	434	425	446	454	450	425	396	350	212
10	408	404	429	434	442	454	433	421	396	350	212
Averages	407	401	434	432	445	452	440	423	396	352	210

Run No. 14 Total Discharge .772 cfs Slope = 2% n = .008											
x	0	1	2	3	4	5	6	7	8	9	10
1	596	605	633	637	625	633	613	584	546	467	292
2	596	600	617	613	629	613	596	567	534	463	288
3	609	609	621	625	633	621	596	571	541	471	288
4	575	588	617	625	655	655	621	579	546	467	288
5	587	605	621	625	617	629	596	558	530	454	292
6	596	605	633	637	625	633	613	584	546	467	292
7	602	600	617	613	629	617	596	567	534	467	288
8	578	594	617	625	633	621	611	575	545	471	292
9	595	605	621	625	655	659	621	575	546	463	292
10	594	607	633	637	625	633	613	584	546	467	292
Averages	593	602	623	626	633	631	608	574	541	466	290

Run No. 15 Total Discharge = .530 cfs

Slope = 2% n = .013

x	0	1	2	3	4	5	6	7	8	9	10
1	454	492	508	529	525	533	512	504	462	408	213
2	450	492	504	533	525	537	516	504	466	412	216
3	454	496	508	533	525	529	516	504	466	408	212
4	454	496	512	533	529	533	516	500	462	412	208
5	458	492	508	529	533	541	512	504	462	408	213
6	458	492	512	533	533	533	516	504	466	408	212
7	454	492	508	537	529	537	512	508	462	408	213
8	458	492	512	533	529	541	512	504	466	408	208
9	454	496	512	533	525	537	516	504	466	404	213
10	458	492	516	537	525	537	516	500	466	408	213
Averages	455	493	510	533	528	536	514	504	464	408	212

Run No. 16 Total Discharge = .767 cfs

Slope = 2% n = .013

x	0	1	2	3	4	5	6	7	8	9	10
1	604	641	667	684	687	687	654	629	579	517	294
2	600	637	671	684	692	683	655	634	579	513	294
3	608	645	667	680	683	683	650	629	579	508	290
4	604	645	667	680	683	683	654	629	575	517	290
5	600	645	671	680	687	679	650	629	579	517	294
6	604	645	667	680	692	679	650	629	579	513	294
7	604	641	663	684	692	679	654	633	579	508	290
8	600	641	663	680	687	683	654	629	575	513	294
9	604	645	667	680	683	683	655	633	579	513	294
10	604	641	667	684	692	679	654	629	583	513	294
Averages	603	643	667	682	688	682	653	630	579	513	293

Run No. 17   Total Discharge = .530 cfs

Slope = 2%   n = .016

x	0	1	2	3	4	5	6	7	8	9	10
1	500	516	542	550	558	546	550	525	488	437	275
2	504	516	546	550	554	550	542	525	479	442	279
3	504	516	546	550	550	546	546	529	484	442	279
4	500	516	542	554	554	550	538	525	488	442	275
5	500	516	546	546	558	542	542	529	484	438	275
6	500	516	546	546	558	538	546	529	484	437	271
7	500	521	550	550	558	546	538	521	484	442	275
8	504	516	542	546	558	554	534	516	479	442	271
9	500	521	542	550	558	550	538	521	484	446	271
10	500	521	542	542	563	554	542	525	479	437	279
Averages	501	518	544	548	557	548	542	525	483	441	275

Run No. 18 Total Discharge = .766 cfs

Slope = 2% n = .016

x	0	1	2	3	4	5	6	7	8	9	10
1	648	663	679	688	696	680	680	663	608	563	329
2	647	663	683	688	696	692	680	663	608	563	329
3	642	663	679	683	700	692	684	655	604	558	333
4	648	667	683	688	696	692	684	659	612	558	325
5	647	663	679	692	696	692	676	663	608	558	329
6	647	663	679	692	700	688	680	663	608	563	333
7	648	663	675	683	696	692	680	663	604	558	325
8	634	663	675	688	696	688	676	659	608	563	329
9	648	663	683	683	700	692	680	659	608	558	329
10	642	663	679	683	696	688	680	663	608	563	333
Averages	645	663	679	687	697	691	680	661	608	561	329

TABLE 3. Experimental Determination of Manning's Roughness Coefficient, n

Depth in Thousandth of a foot

x = Distance from upstream end, feet

$$n = \frac{1.49\ A\ R^{2/3}\ S^{1/2}}{Q} = \text{Manning Roughness Coefficient}$$

A = Cross-sectional area

R = Hydraulic radius

S = Channel bottom slope

Q = Discharge

Run No. 1 Varnished Plywood Channel

Discharge = .103 cfs

Slope = .0025

x	2	3	4	5	6	7	8	9	10	11	12	13
Depth	128	126	124	122	124	125	123	116	112	110	102	092

Assume uniform depth = .124 feet

Therefore n = .00843

Run No. 2 Varnished Plywood Channel

Discharge = .260 cfs

Slope = .0025

x	2	3	4	5	6	7	8	9	10	11	12	13
Depth	245	237	234	232	237	236	233	224	217	207	199	182

Assume uniform depth = .234 feet

Therefore n = .00818

Run No. 3 Varnished Plywood Channel

Discharge = .115 cfs

Slope = .0020

x	2	3	4	5	6	7	8	9	10	11	12	13
Depth	143	144	143	147	143	147	144	135	132	131	118	111

Assume uniform depth = .145 feet

Therefore n = .0086

Run No. 4 Varnished Plywood Channel

Discharge = .251 cfs

Slope = .0020

x	2	3	4	5	6	7	8	9	10	11	12	13
Depth	241	235	238	238	241	242	236	226	223	212	198	181

Assume uniform depth = .239 feet

Therefore n = .00785

Run No. 5 Varnished Plywood with Screen Wire

Discharge = .103 cfs

Slope = .0025

x	2	3	4	5	6	7	8	9	10	11	12	13
Depth	187	185	183	181	181	179	173	165	157	151	137	122

Assume uniform depth = .181 feet

Therefore n = .0145

Run No. 6 Varnished Plywood with Screen Wire

Discharge = .260 cfs

Slope = .0025

x	2	3	4	5	6	7	8	9	10	11	12	13
Depth	337	331	323	321	319	308	295	282	268	258	240	215

Assume uniform depth = .321 feet

Therefore n = .0124

Run No. 7 Varnished Plywood with Wooden Cubes

Discharge = .115 cfs

Slope = .0020

x	2	3	4	5	6	7	8	9	10	11	12	13
Depth	238	235	235	236	229	226	220	215	208	198	184	167

Assume uniform depth = .235 feet

Therefore n = .0167

Run No. 8 Varnished Plywood with Wooden Cubes

Discharge = .251 cfs

Slope = .0020

x	2	3	4	5	6	7	8	9	10	11	12	13
Depth	351	347	347	348	338	329	322	311	302	290	268	247

Assume uniform depth = .347

Therefore n = .0128

TABLE 4. Theoretical Nondimensional Flow Profiles for Spatially Varied Flow with Uniform Inflow.

y/y_o = Depth divided by critical depth.

x/L = Distance from upstream end divided by the total length of the channel.

Rectangular channel ten feet long and six inches wide.

Slope = 0% n = 0.02			
Total Discharge = 0.530 cfs		Total Discharge = 0.767 cfs	
x/L	y/y_o	x/L	y/y_o
0	1.79	0	1.78
0.1	1.78	0.1	1.77
0.2	1.77	0.2	1.76
0.3	1.75	0.3	1.75
0.4	1.73	0.4	1.72
0.5	1.69	0.5	1.69
0.6	1.65	0.6	1.64
0.7	1.59	0.7	1.58
0.8	1.50	0.8	1.50
0.9	1.38	0.9	1.38
1.0	1.00	1.0	1.00

Slope = 1% n = 0.02			
Total Discharge = 0.530 cfs		Total Discharge = 0.766 cfs	
x/L	y/y_o	x/L	y/y_o
0	1.49	0	1.55
0.1	1.51	0.1	1.57
0.2	1.53	0.2	1.58
0.3	1.54	0.3	1.59
0.4	1.55	0.4	1.60
0.5	1.56	0.5	1.58
0.6	1.54	0.6	1.56
0.7	1.50	0.7	1.51
0.8	1.44	0.8	1.45
0.9	1.34	0.9	1.35
1.0	1.00	1.0	1.00

Slope = 2%		n = 0.02	
Total Discharge = 0.524 cfs		Total Discharge = 0.772 cfs	
x/L	y/y_o	x/L	y/y_o
0	1.18	0	1.29
0.1	1.24	0.1	1.34
0.2	1.28	0.2	1.37
0.3	1.32	0.3	1.40
0.4	1.35	0.4	1.42
0.5	1.38	0.5	1.43
0.6	1.40	0.6	1.44
0.7	1.41	0.7	1.44
0.8	1.37	0.8	1.40
0.9	1.30	0.9	1.31
1.0	1.00	1.0	1.00

TABLE 5. Theoretical Nondimensional Flow Profiles for Spatially Varied Flow with Inflow Varying In A Triangular Pattern.

y/y_o = Depth divided by critical depth.

x/L = Distance from upstream end divided by the total length of the channel.

Rectangular channel ten feet long and six inches wide.

Slope = 0% n = 0.01			
Total Discharge = 0.530 cfs		Total Discharge = 0.766 cfs	
x/L	y/y_o	x/L	y/y_o
0	1.75	0	1.75
0.1	1.75	0.1	1.75
0.2	1.75	0.2	1.75
0.3	1.74	0.3	1.74
0.4	1.72	0.4	1.72
0.5	1.66	0.5	1.66
0.6	1.57	0.6	1.57
0.7	1.46	0.7	1.46
0.8	1.33	0.8	1.33
0.9	1.18	0.9	1.18
1.0	1.00	1.0	1.00

Slope = 1%		n = 0.01	
Total Discharge = 0.535 cfs		Total Discharge = 0.771 cfs	
x/L	y/y_o	x/L	y/y_o
0	1.48	0	1.54
0.1	1.51	0.1	1.56
0.2	1.54	0.2	1.58
0.3	1.56	0.3	1.59
0.4	1.57	0.4	1.60
0.5	1.53	0.5	1.56
0.6	1.46	0.6	1.48
0.7	1.36	0.7	1.38
0.8	1.25	0.8	1.26
0.9	1.11	0.9	1.12
1.0	1.00	1.00	1.00

Slope = 2%		n = 0.01	
Total Discharge = 0.524		Total Discharge = 0.772 cfs	
x/L	y/y_o	x/L	y/y_o
0	1.21	0	1.33
0.1	1.27	0.1	1.38
0.2	1.33	0.2	1.43
0.3	1.38	0.3	1.46
0.4	1.41	0.4	1.48
0.5	1.42	0.5	1.46
0.6	1.36	0.6	1.39
0.7	1.27	0.7	1.30
0.8	1.17	0.8	1.19
0.9	0.98	0.9	0.99
1.0	1.00	1.0	1.00

XV111. APPENDIX C:

Digital Computer Program for Spatially Varied Flow

```
$ID   JOHNSON,R.W. SPATIALLY VARIED FLOW, UNIFORM INFLOW
$IBFTC
C     DIST = TOTAL CHANNEL LENGTH
C     WIDTH = CHANNEL WIDTH
C     CHSL = CHANNEL BOTTOM SLOPE
C     RC = MANNING ROUGHNESS COEFFICIENT
C     DELTA = NUMBER OF CHANNEL INCREMENTS USED
C     QFT = UNIFORM INFLOW PER FOOT OF CHANNEL LENGTH
C     VBAR = VELOCITY AT SOME POINT DIVIDED BY CRITICAL
C            VELOCITY
C     DBAR = DEPTH AT SOME POINT DIVIDED BY CRITICAL DEPTH
C     QBAR = DISCHARGE AT SOME POINT DIVIDED BY CRITICAL
C            DISCHARGE
C     DDELB = CHANGE IN DEPTH BETWEEN SECTIONS DIVIDED BY
C            CRITICAL DEPTH
C     QDELB = CHANGE IN FLOW BETWEEN SECTIONS DIVIDED BY
C            CRITICAL FLOW
C     AREAC = CRITICAL AREA
C     DEPC = CRITICAL DEPTH
C     RADBAR = HYDRAULIC RADIUS AT CRITICAL SECTION DIVIDED
C            BY CRITICAL DEPTH
C     QC = CRITICAL DISCHARGE
C     VC = CRITICAL VELOCITY
C     SFR = FRICTION SLOPE IN MANNING EQUATION
C     DISBAR = CHANNEL LENGTH DIVIDED BY CRITICAL DEPTH
```

```
C       BSLC = CHANNEL SLOPE TIMES INCREMENT LENGTH DIVIDED
C               BY CRITICAL DEPTH
C       CONST = A CONSTANT,PART OF MANNING FORMULA
C       ASFR = FIRST APPROXIMATION FOR FRICTION SLOPE
C       ADDELB = FIRST APPROXIMATION FOR CHANGE IN DEPTH
C       ANS = THEORETICAL DEPTH
      1 READ(5,5) DIST,WIDTH,CHSL,QFT,RC,DELTA
      5 FORMAT(6F9.4)
        DIMENSION VBAR(30),DBAR(30),QBAR(30),DDELB(30),ANS(30)
        DEPC = (((QFT*DIST)/WIDTH)**2/32.2)**(0.33333333)
        AREAC = DEPC*WIDTH
        RADBAR = AREAC/(DEPC*(2.*DEPC+WIDTH))
        QC = QFT*DIST
        VC = QC/AREAC
        DISBAR = DIST/DEPC
        BSLC = CHSL*DISBAR/DELTA
        CONST = (RC*RC*VC*VC)/(2.22*(DEPC*RADBAR)**1.333)
        I = 1
        VBAR(I) = 1.0
        DBAR(I) = 1.0
        QBAR(I) = 1.0
        ANS(I) = DEPC
        QDELB = 1.0/DELTA
        K = DELTA
        DO 40 I = 1,K,1
```

```
      ASFR = CONST*VBAR(I)*VBAR(I)/(DBAR(I)**1.333)
      QBAR(I+1) = QBAR(I)-QDELB
      ADDELB = BSLC-(ASFR*DISBAR/DELTA)-(QBAR(I+1)*2.
     1        *VBAR(I))/(QBAR(I+1)+QBAR(I))*(VBAR(I)*
     2        QDELB/QBAR(I+1))
      IF(ADDELB)15,40,35
   15 DBAR(I+1) = DBAR(I)-ADDELB
   30 TRIAL = DBAR(I+1)
      ANS(I+1) = DBAR(I+1)*DEPC
      VBAR(I+1) = QBAR(I+1)/DBAR(I+1)
      SFR = CONST*VBAR(I+1)*VBAR(I+1)/(DBAR(I+1)**1.333)
      DDELB(I) = BSLC-(SFR*DISBAR/DELTA)-(QBAR(I+1)*
     1        (VBAR(I+1)+VBAR(I))/(QBAR(I+1)+QBAR(I))*
     2        (VBAR(I)-VBAR(I+1)+VBAR(I)*QDELB/QBAR(I+1)))
      DBAR(I+1) = DBAR(I)-DDELB(I)
      TEST = DBAR(I+1)-(TRIAL+.001)
   55 IF(TEST)10,20,30
   10 DBAR(I+1) = TRIAL
      DDELB(I) = DBAR(I)-DBAR(I+1)
      GO TO 40
   20 DBAR(I+1) = TRIAL+.001
      DDELB(I) = DBAR(I)-DBAR(I+1)
      GO TO 40
   35 DBAR(I+1) = DBAR(I)-ADDELB
   45 TRIAL = DBAR(I+1)
```

```
      ANS(I+1) = DBAR(I+1)*DEPC
      VBAR(I+1) = QBAR(I+1)/DBAR(I+1)
      SFR = CONST*VBAR(I+1)*VBAR(I+1)/(DBAR(I+1)**1.333)
      DDELB(I) = BSLC-(SFR*DISBAR/DELTA)-(QBAR(I+1)*
     1        (VBAR(I+1)+VBAR(I))/(QBAR(I+1)+QBAR(I))*
     2        (VBAR(I)-VBAR(I+1)+VBAR(I)*QDELB/QBAR(I+1)))
      DBAR(I+1) = DBAR(I)-DDELB(I)
      TEST = -DBAR(I+1) + (TRIAL+.001)
      GO TO 55
   40 CONTINUE
      WRITE(6,50)DIST,WIDTH,CHSL
   50 FORMAT(21X,36H DIMENSIONLESS WATER SURFACE PROFILE,
     1 1X,43H FOR SPATIALLY VARIED FLOW IN A RECTANGULAR,
     2 1X,8H CHANNEL///33X,18H CHANNEL LENGTH = ,F10.4,
     3 6H FEET /33X,17H CHANNEL WIDTH = ,F10.4,6H FEET/
     4 33X,17H CHANNEL SLOPE = ,F10.4/)
      WRITE(6,52)QFT
   52 FORMAT(33X,18H UNIFORM INFLOW = ,F10.4,
     1 43H CUBIC FEET PER SECOND PER FOOT OF CHANNEL  /)
      WRITE(6,100)RC,DELTA
  100 FORMAT(33X,33H MANNING ROUGHNESS COEFFICIENT = ,
     1 F10.4/33X,36H THE CHANNEL LENGTH IS DIVIDED INTO ,
     2 F10.4,2X,8HSECTIONS////20X,7H DDELB ,5X,7H  DBAR ,
     3 5X,9H     VBAR,5X,15H CRITICAL DEPTH ,5X,
     418H CRITICAL VELOCITY,5X,18H THEORETICAL DEPTH/)
```

```
      I = 1
      WRITE(6,60)DBAR(I),VBAR(I),DEPC,VC,ANS(I)
60    FORMAT(30X,F10.4,5X,F10.4,5X,F10.4,5X,F10.4,15X,F10.4)
      DO 70 I = 1,K,1
      J = I+1
      WRITE(6,80)DDELB(J),DBAR(J),VBAR(J),ANS(J)
80    FORMAT(15X,F10.4,5X,F10.4,5X,F10.4,45X,F10.4)
70    CONTINUE
      GO TO 1
90    STOP
      END
```

```
$ID    JOHNSON,R.W. SPATIALLY VARIED FLOW, NONUNIFORM INFLOW
$IBFTC
C      DIST = TOTAL CHANNEL LENGTH
C      WIDTH = CHANNEL WIDTH
C      CHSL = CHANNEL BOTTOM SLOPE
C      RC = MANNING ROUGHNESS COEFFICIENT
C      DELTA = NUMBER OF CHANNEL INCREMENTS USED
C      QCT = TOTAL DISCHARGE, ALSO EQUAL TO CRITICAL FLOW
C      VBAR = VELOCITY AT SOME POINT DIVIDED BY CRITICAL
C             VELOCITY
C      DBAR = DEPTH AT SOME POINT DIVIDED BY CRITICAL DEPTH
C      QBAR = DISCHARGE AT SOME POINT DIVIDED BY CRITICAL
C             DISCHARGE
C      DDELB = CHANGE IN DEPTH BETWEEN SECTIONS DIVIDED BY
C             CRITICAL DEPTH
C      QDELB = CHANGE IN FLOW BETWEEN SECTIONS DIVIDED BY
C             CRITICAL FLOW
C      AREAC = CRITICAL AREA
C      DEPC = CRITICAL DEPTH
C      RADBAR = HYDRAULIC RADIUS AT CRITICAL SECTION DIVIDED
C             BY CRITICAL DEPTH
C      QC = CRITICAL DISCHARGE
C      VC = CRITICAL VELOCITY
C      SFR = FRICTION SLOPE IN MANNING EQUATION
C      DISBAR = CHANNEL LENGTH DIVIDED BY CRITICAL DEPTH
```

```
C      BSLC = CHANNEL SLOPE TIMES INCREMENT LENGTH DIVIDED
C             BY CRITICAL DEPTH
C      CONST = A CONSTANT,PART OF MANNING FORMULA
C      ASFR = FIRST APPROXIMATION FOR FRICTION SLOPE
C      ADDELB = FIRST APPROXIMATION FOR CHANGE IN DEPTH
C      Q = TOTAL DISCHARGE DIVIDED BY CHANNEL LENGTH
C      ANS = THEORETICAL DEPTH
     1 READ(5,5) DIST,WIDTH,CHSL,QCT,RC,DELTA
     5 FORMAT(6F9.4)
       DIMENSION VBAR(30),DBAR(30),QBAR(30),DDELB(30),
      1 ANS(30),X(30),DELQ(30)
       DEPC = ((QCT/WIDTH)**2/32.2)**0.33333333
       AREAC = DEPC*WIDTH
       RADBAR = AREAC/(DEPC*(2.*DEPC+WIDTH))
       QC = QCT
       VC = QC/AREAC
       DISBAR = DIST/DEPC
       BSLC = CHSL*DISBAR/DELTA
       CONST = (RC*RC*VC*VC)/(2.22*(DEPC*RADBAR)**1.333)
       Q = QC/DIST
       I = 1
       VBAR(I) = 1.0
       DBAR(I) = 1.0
       QBAR(I) = 1.0
       ANS(I) = DEPC
```

```
      X(I) = DIST
      DELQ(I) = 0.0
      K = DELTA
      DO 40 I = 1,K,1
      ASFR = CONST*VBAR(I)*VBAR(I)/(DBAR(I)**1.333)
      X(I+1) = X(I)-(DIST/DELTA)
      CHECK = X(I+1)-(DIST/2.0)
      IF(CHECK)110,120,120
  110 QDELB = 2.0*Q/(DIST*QC)*(X(I)*X(I)-X(I+1)*X(I+1))
      GO TO 25
  120 QDELB = (2.0*Q/(DIST*QC)*(DIST-X(I+1))**2)-(2.0*Q/
     1 (DIST*QC)*(DIST-X(I))**2.0)
   25 QBAR(I+1) = QBAR(I)-QDELB
      DELQ(I+1) = QDELB
      ADDELB = BSLC-(ASFR*DISBAR/DELTA)-(QBAR(I+1)*2.
     1         *VBAR(I))/(QBAR(I+1)+QBAR(I))*(VBAR(I)*
     2         QDELB/QBAR(I+1))
      IF(ADDELB)15,40,35
   15 DBAR(I+1) = DBAR(I)-ADDELB
   30 TRIAL = DBAR(I+1)
      ANS(I+1) = DBAR(I+1)*DEPC
      VBAR(I+1) = QBAR(I+1)/DBAR(I+1)
      SFR = CONST*VBAR(I+1)*VBAR(I+1)/(DBAR(I+1)**1.333)
      DDELB(I) = BSLC-(SFR*DISBAR/DELTA)-(QBAR(I+1)*
     1         (VBAR(I+1)+VBAR(I))/(QBAR(I+1)+QBAR(I))*
```

```
  2         (VBAR(I)-VBAR(I+1)+VBAR(I)*QDELB/QBAR(I+1)))
      DBAR(I+1) = DBAR(I)-DDELB(I)
      TEST = DBAR(I+1)-(TRIAL+.001)
   55 IF(TEST)10,20,30
   10 DBAR(I+1) = TRIAL
      DDELB(I) = DBAR(I)-DBAR(I+1)
      GO TO 40
   20 DBAR(I+1) = TRIAL+.001
      DDELB(I) = DBAR(I)-DBAR(I+1)
      GO TO 40
   35 DBAR(I+1) = DBAR(I)-ADDELB
   45 TRIAL = DBAR(I+1)
      ANS(I+1) = DBAR(I+1)*DEPC
      VBAR(I+1) = QBAR(I+1)/DBAR(I+1)
      SFR = CONST*VBAR(I+1)*VBAR(I+1)/(DBAR(I+1)**1.333)
      DDELB(I) = BSLC-(SFR*DISBAR/DELTA)-(QBAR(I+1)*
  1         (VBAR(I+1)+VBAR(I))/(QBAR(I+1)+QBAR(I))*
  2         (VBAR(I)-VBAR(I+1)+VBAR(I)*QDELB/QBAR(I+1)))
      DBAR(I+1) = DBAR(I)-DDELB(I)
      TEST = -DBAR(I+1)+(TRIAL+.001)
      GO TO 55
   40 CONTINUE
      WRITE(6,50)DIST,WIDTH,CHSL
   50 FORMAT(21X,36H DIMENSIONLESS WATER SURFACE PROFILE,
  1 1X,43H FOR SPATIALLY VARIED FLOW IN A RECTANGULAR,
```

```
  2 1X,8H CHANNEL///33X,18H CHANNEL LENGTH = ,F10.4,
  3 6H FEET /33X,17H CHANNEL WIDTH = ,F10.4,6H FEET/
  4 33X,17H CHANNEL SLOPE = ,F10.4/)
    WRITE(6,100)RC,DELTA
100 FORMAT(33X,33H MANNING ROUGHNESS COEFFICIENT = ,
  1 F10.4/33X,36H THE CHANNEL LENGTH IS DIVIDED INTO ,
  2 F10.4,2X,8HSECTIONS////20X,5HDDELB,5X,4HDBAR,5X,
  3 4HVBAR,2X,14HCRITICAL DEPTH,3X,17HCRITICAL VELOCITY,
  4 4X,17HTHEORETICAL DEPTH,6X,5HQDELB/)
    I = 1
    WRITE(6,60)DBAR(I),VBAR(I),DEPC,VC,ANS(I)
 60 FORMAT(30X,F10.4,5X,F10.4,5X,F10.4,5X,F10.4,15X,F10.4)
    DO 70 I = 1,K,1
    J = I+1
    WRITE(6,80)DDELB(J),DBAR(J),VBAR(J),ANS(J),DELQ(J)
 80 FORMAT(15X,F10.4,5X,F10.4,5X,F10.4,45X,F10.4,2X,F10.4)
 70 CONTINUE
    GO TO 1
 90 STOP
    END
```

ABSTRACT

The fundamental differential equation for spatially varied flow with increasing discharge is altered to a dimensionless form. The solution of this equation gives a nondimensional profile from which flow profiles can be obtained.

A digital computer program is included for solving the nondimensional equation for the condition of constant incremental inflow. Experimental results, using various channel roughness values, are included in order to verify the accuracy of the nondimensional equation.

Another digital computer program is included for solving the nondimensional equation when the incremental inflow varies in a triangular shape.