

# MEASUREMENT DEVICE EFFECT ON CHANNEL WATER LOSS

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**ABSTRACT:** Flow measurement devices can cause significant errors in inflow-outflow channel water loss measurements. The device effects, caused by the increased water surface elevation upstream of a device, must be subtracted from measured losses to correctly estimate conveyance water loss. Methods to calculate device effects are given. In channels with small slopes and in which loss rates increase sharply with water surface increases, inflow-outflow loss measurements should be made in long channel sections with devices which create as little head loss as possible.

## INTRODUCTION

A common method of measuring water loss from conveyance channels is the inflow-outflow method (3,8) in which the inflow rate to the head and outflow rate from the tail of a channel section are measured. The difference in the two flow rates is the flow loss,  $Q_L$ , or volumetric water loss per unit time, in the section. The flow loss can be converted to a loss rate per unit length of channel or to a seepage rate (flow loss per unit wetted area) to allow a comparison among channels and to evaluate the need for channel improvements.

Extensive conveyance loss measurements were made by the inflow-outflow method in unlined watercourses (laterals) in the Indus Basin of Pakistan (2,5,7). These data demonstrated an unexpected relationship between the length of channel section measured and the loss rate (10). As successively shorter sections of a given channel were measured, the measured loss rate (or seepage rate) increased. Similarly, outflow rates measured progressively closer to the inflow measurement point tended toward a projected flow value at the inflow device below the measured inflow rate. These phenomena are graphically demonstrated in Fig. 1.

Since this trend was not related to the physical condition of the channels and only a small and predictable portion could have been caused by decreasing flow rates (resulting from higher loss) in longer channels, it was concluded that the measurement process must in some way affect the water loss.

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Note.—Discussion open until August 1, 1983. To extend the closing date one month, a written request must be filed with the ASCE Manager of Technical and Professional Publications. The manuscript for this paper was submitted for review and possible publication on July 29, 1982. This paper is part of the *Journal of Irrigation and Drainage Engineering*, Vol. 109, No. 1, March, 1983. ©ASCE, ISSN 0733-9437/83/0001-0060/\$01.00. Proc. No. 17804.

### CAUSE OF MEASUREMENT DEVICE EFFECTS

Extensive ponding loss measurements in the Pakistan watercourses consistently exhibited a strong positive exponential relationship between changing flow depth in a channel and the loss rate (1,10). Measurements in Colorado and New Mexico unlined laterals have shown a similar loss rate vs. depth relationship (1,6). The causes of this relationship include: (1) Increased wetted area with increasing flow depth; (2) increased hydrostatic pressure at the water-soil boundary with increasing depth; and (3) a higher permeability of upper bank soils compared to bed soils due to a lack of sediment deposition and an extremely high porosity caused by insect and rodent burrowing and decayed root channels. The most important of these three factors is the last. Seepage rates (loss per unit wetted area) into upper bank soils are often more than 10 times higher than seepage rates into the channel beds (10).

Flow rates in small channels are usually measured with devices such as flumes, weirs, and orifices, which create a measurable energy conversion in the flow. The Pakistan watercourse losses were measured with portable cutthroat flumes (9). All of these devices cause several centimeters of energy or head loss in the flowing water, with most requiring at least 60 mm to 100 mm (2-1/2 in. to 4 in.) of head loss to operate as designed. A flow measurement device which creates a head loss will raise the water level upstream of the device (in subcritical flow), and the raised level will extend for some distance upstream. Based on the loss rate vs. depth relationship previously described, such devices would be

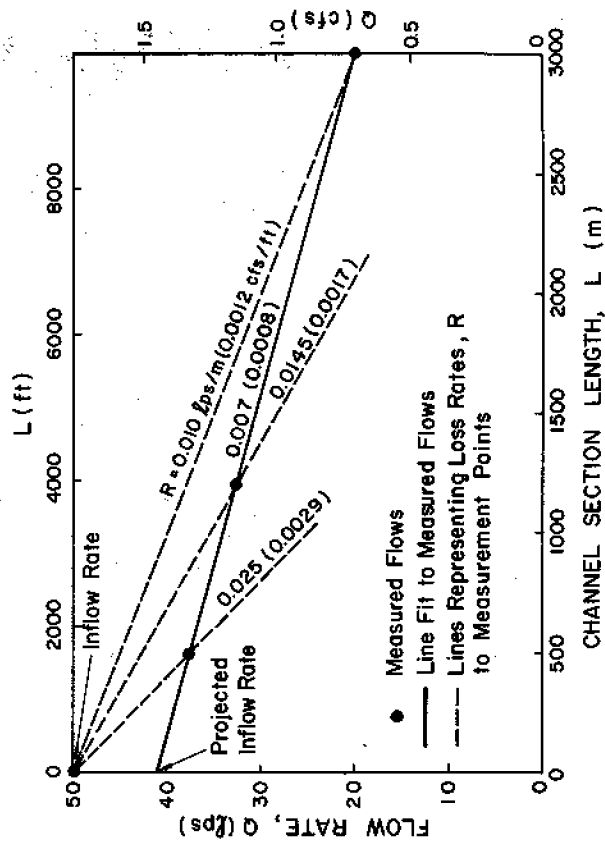


FIG. 1.—Typical Inflow-Outflow Measurements Showing Projected Inflow Rate Below Actual Rate, and Increasing Loss Rates,  $R$ , with Decreasing Section Length

expected to increase the water loss from the upstream channel. Thus, the outflow measurement device will increase losses in a measured channel reach.

### ESTIMATING DEVICE EFFECTS

The effect of the measurement process on the water loss can be estimated from a calculation of the raised water level upstream of the outflow measurement device, and the relationship between loss rate and flow depth changes (which can be determined by ponding measurements). The raised water level in the channel section can be determined, if the flow is steady and uniform, by a backwater curve calculation. The backwater water surface profile will depend upon the channel hydraulic characteristics: cross-sectional flow area,  $A$ , wetted perimeter length,  $P$ , slope,  $S$ , roughness coefficient,  $n$ , and flow rate,  $Q$  (or the hydraulic normal depth,  $D_n$ , from which the flow rate can be derived); and the amount the water surface level is raised above the normal flow depth at the measurement device,  $D_o$ .

Backwater curve calculations were made iteratively by the direct step method (4). The Manning's formula was used to determine the friction slope. The channel cross-sectional shape was modeled by a power curve of the form:

$$T = 2 C_1 D^{C_2} \dots \dots \dots (1)$$

in which  $T$  = water surface width;  $D$  = water depth; and  $C_1$ ,  $C_2$  = empirical coefficients dependent on the channel shape. Fig. 2 illustrates the wide range of cross-sectional shapes which can be described by Eq. 1. The empirical exponent,  $C_2$ , determines the general shape, which can vary from triangular to nearly rectangular, while the coefficient,  $C_1$ , determines the relative horizontal to vertical scales.

The channel cross-sectional area,  $A$ , was determined by integrating

$$A = \int_0^D 2C_1 d^{C_2} dd = \frac{2C_1}{C_2 + 1} D^{C_2 + 1} \dots \dots \dots (2)$$

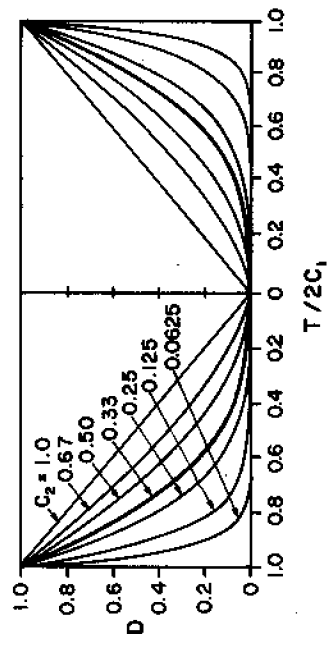


FIG. 2.—Channel Cross-Sectional Shapes which Can be Described by  $T = 2 C_1 D^{C_2}$  (Eq. 1)

The wetted perimeter length,  $P$ , was determined by calculating twice the line integral of the Eq. 1 along half the water surface width.

$$P = 2 \int_0^D \left[ 1 + \frac{d^2 \left( \frac{F}{2} \right)^2}{dd^2} \right]^{1/2} dd = 2 \int_0^D \left[ 1 + (C_1 C_2 d^{C_2-1})^2 \right]^{1/2} dd \dots \dots \dots (3)$$

This integral was evaluated numerically using Simpson's Rule.

The relationship between water loss and flow depth is exponential of the form (1,10):

$$Q_L = Q_{LO} e^{B(D-D_n)} \dots \dots \dots (4)$$

in which  $Q_L$  = the water loss (same units as  $Q_{LO}$ );  $Q_{LO}$  = the water loss when the channel is flowing at the usual depth,  $D_n$ ;  $B$  = an empirical coefficient representing the fractional increase in  $Q_L$  with a unit change in  $D$  (inverse units of  $D$ );  $D$  = the flow depth; and  $D_n$  = the usual flow depth, taken here as the hydraulic normal depth (same units as  $D$ ). This relationship has been found to be valid in most small channels for  $D = D_n \pm 0.1$  m (4 in.). By dividing both sides of Eq. 4 by  $Q_{LO}$ , a relative loss,  $Q_L/Q_{LO}$ , resulting from the change in flow depth is determined. Fig. 3 illustrates this functional relationship. Measured values of the exponent,  $B$ , in watercourses generally varied between  $10 \text{ m}^{-1}$  and  $20 \text{ m}^{-1}$  ( $3 \text{ ft}^{-1}$  and  $6 \text{ ft}^{-1}$ ) and averaged  $15 \text{ m}^{-1}$  ( $4.6 \text{ ft}^{-1}$ ). This average rate predicts a doubling of the loss with  $0.05$  m (2 in.) increase in the flow depth.

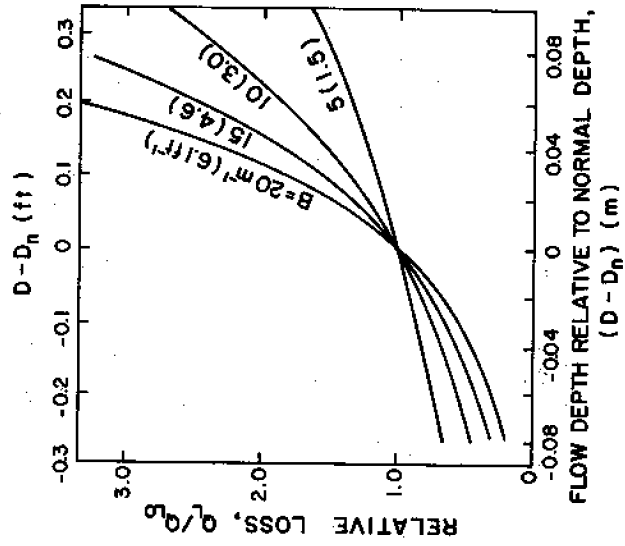


FIG. 3.—Exponential Relationship between Relative Water Loss and Flow Depth Changes (Eq. 4)

The relative loss at any point along the measured channel section was calculated by inserting the increased flow depth ( $D - D_n$ ) at any distance upstream of the flow measurement device, determined by the backwater calculation, into Eq. 4. The relative loss for a measured channel section was then determined by calculating the length weighted average relative loss for the section. This was done by numerically integrating Eq. 4 over the measured length and dividing by the length.

$$F = \frac{\left[ \int_0^L e^{B(D-D_n)} d\ell \right]}{L} \dots \dots \dots (5)$$

in which  $F$  = the relative loss,  $Q_L/Q_{LO}$ , for a particular channel section of length,  $L$  (also called the device effects factor). This relative loss or device effects factor is plotted for typical input values in Fig. 4. The importance of these device effects, especially in channels with small slopes and when short channel sections are measured, is evident from the figure.

The extra water loss caused by a given flow measurement device installed in a particular channel will approach a maximum value at a distance upstream of the device where the water depth approaches normal depth. Beyond this backwater length,  $L_M$ , the device will cause no additional loss. This absolute extra loss ( $Q_L - Q_{LO}$ ), which is directly related to the average original (without the device) loss rate in the channel,  $R_0$ , can be calculated by:

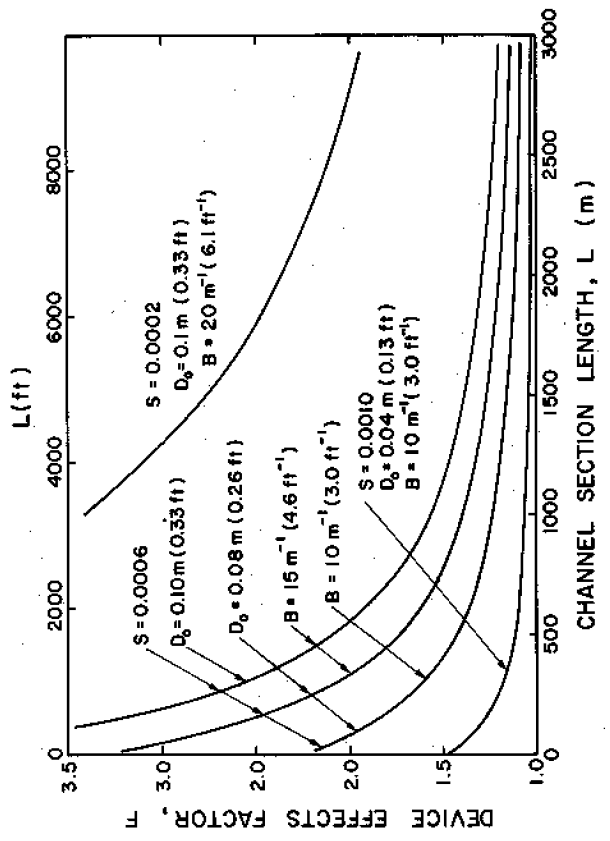


FIG. 4.—Relative Loss (Device Effects Factor) versus Channel Length for Five Combinations of Slope,  $S$ , Device Head Loss,  $D_0$ , and Loss versus Depth Coefficient,  $B$ , in Channel with Normal Flow Depth of  $0.4$  m (1.1 ft)

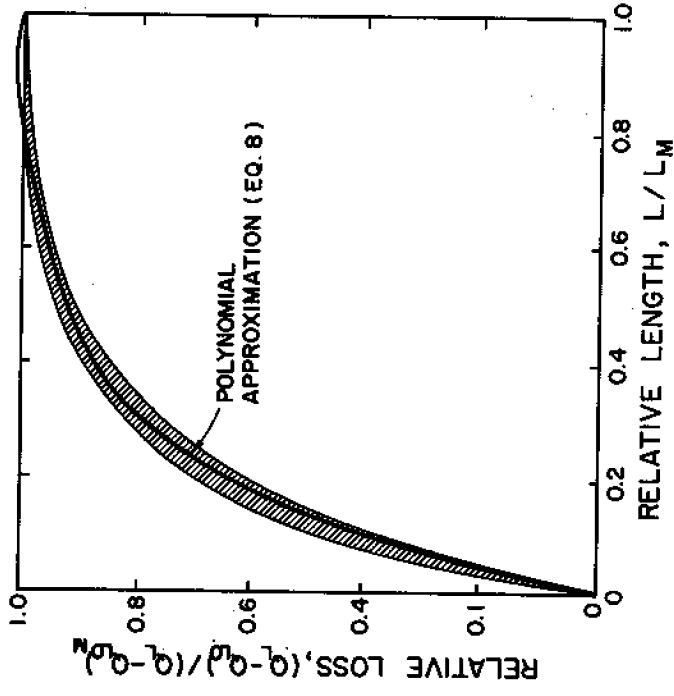


FIG. 6.—Relative Loss versus Relative Length. Envelope Encloses All Values Generated from all Combinations of Parameters Listed in Table 1

solvable approximation for measurement device effects was developed to make the analysis more practical. A direct approximation for backwater profiles in a form which allows Eq. 4 to be directly integrated was not found. Alternatively, the device effects relationship was empirically modeled using regression techniques.

The absolute water loss relationship (Eq. 6) was modeled instead of the device effects factor (Eq. 5) because the section length,  $L$ , could be removed from this relationship. The device induced total loss asymptotically approaches a maximum value,  $(Q_L - Q_{LO})_M$ , as  $L$  approaches the backwater profile length,  $L_M$ . When the induced loss in a shorter channel divided by the total length of the backwater profile,  $L/L_M$ , all values fall within the envelope depicted in Fig. 6. No such normalized value varies from the midpoint of the envelope by more than 10%. Thus, only two values, the maximum loss and the backwater length, need to be determined to closely approximate Eq. 6.

The values in the envelope depicted in Fig. 6 can be modeled closely with a fourth degree polynomial:

$$\frac{Q_L - Q_{LO}}{(Q_L - Q_{LO})_M} = 0.0026 + 4.81 \frac{L}{L_M} - 9.87 \left(\frac{L}{L_M}\right)^2 + 9.56 \left(\frac{L}{L_M}\right)^3 - 3.50 \left(\frac{L}{L_M}\right)^4 \dots \dots \dots (8)$$

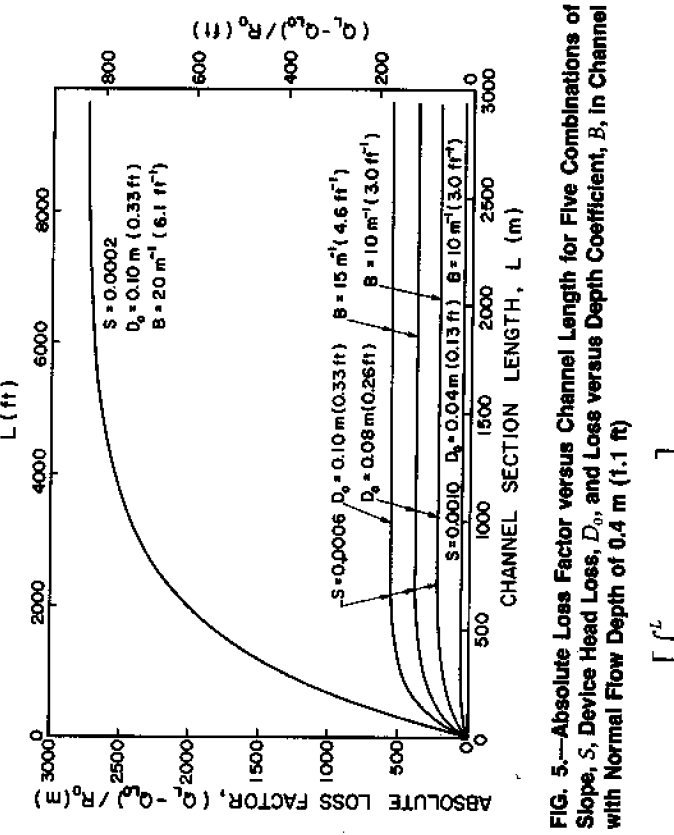


FIG. 5.—Absolute Loss Factor versus Channel Length for Five Combinations of Slope,  $S$ , Device Head Loss,  $D_0$ , and Loss versus Depth Coefficient,  $B$ , in Channel with Normal Flow Depth of 0.4 m (1.1 ft)

Fig. 5 shows this relationship for typical channels and demonstrates its asymptotic nature. Equations 5 and 6 are related by:

$$F = \left[ \frac{Q_L - Q_{LO}}{R_0} \right] \frac{1}{L} + 1 \dots \dots \dots (7)$$

The backwater depths in this analysis were calculated assuming that no water loss occurs in the channel section. Water loss from the channel will progressively decrease flow rates and flow depths. The decreased depths will not have a large effect on the shape of the backwater profile. However, the extra water loss caused by the measurement device installation will decrease the normal flow depth below that which would otherwise occur and thus decrease the absolute amount that which would be caused by the device, and the resultant loss caused by the device. The above calculations will thus overestimate the device effects.

Iterative device effect calculations, in which the flow depths were adjusted for flow rate decreases, were made to determine the amount of this overestimation. The calculations indicated that the device effect overestimation ranges from a few percent for moderate to steeply sloped channels to as high as 30% for channels with small slopes, high loss rates and a strong relationship between depth and loss (a high  $B$  value). For most practical applications, the overestimation will be less than 10%.

**DIRECT APPROXIMATIONS OF DEVICE EFFECTS**

Because of the recursive nature of backwater calculations, a directly

**TABLE 1.—Input Variable Values Used to Generate Data for Regression Analysis**

Independent variable (1)	Variable Values						
	Minimum (2)	(3)	(4)	(5)	(6)	Maximum (8)	
$S$	0.0002	0.0004	0.0006	0.0008	0.0010	0.0012	0.0014
$D_n$ , in meters (feet)	0.30 (0.98)	0.35 (1.15)	0.40 (1.13)	0.40 (1.13)	0.40 (1.13)	0.40 (1.13)	0.45 (1.48)
$D_0$ , in meters (feet)	0.40 (0.13)	0.05 (0.16)	0.06 (0.20)	0.07 (0.23)	0.08 (0.26)	0.09 (0.30)	0.10 (0.33)
$B$ , in meters <sup>-1</sup> (feet <sup>-1</sup> )	10 (3.0)	12.5 (3.8)	15 (4.6)	17.5 (5.3)	20 (6.1)		22.5 (6.9)

The total length of the backwater profile was taken as the distance up-stream of the measurement device where the water surface comes to within 0.00125 m (0.0041 ft) of the normal depth. At this depth, device effects are negligible.

Direct approximations for the backwater length and maximum loss were developed using regression techniques on data generated by the recursive procedure described in the previous section. Data were generated for all combinations of the input variables listed in Table 1. Initial analysis indicated that backwater profiles and thus device effects are insensitive to the channel shape coefficients,  $C_1$  and  $C_2$ , and the roughness coefficient,  $n$ . These input variables were thus dropped from the analysis and constant values, typical of small earthen channels, of  $C_1 = 0.80$ ,  $C_2 = 0.33$ , and  $n = 0.04$  were used.

The effect of the input variables on both backwater length and maximum loss is multiplicative, so the variables were logarithmically transformed before being multilinearly regressed. The length,  $L_M$ , varies with the channel slope,  $S$ , normal flow depth,  $D_n$ , and the amount the depth is increased at the device,  $D_0$

$$L_M = K_1 S^{-1.016} D_n^{0.95} D_0^{0.988} \dots \dots \dots (9)$$

where  $K_1 = 1.40$  when the lengths are expressed in meters and 1.32 when they are given in feet. The coefficient of determination,  $r^2$ , for the relationship is 0.999. The maximum deviation from the generated data is 2%.

Likewise the maximum loss,  $(Q_L - Q_{LO})_M/R_0$ , varies with the previous three input variables plus the exponent,  $B$

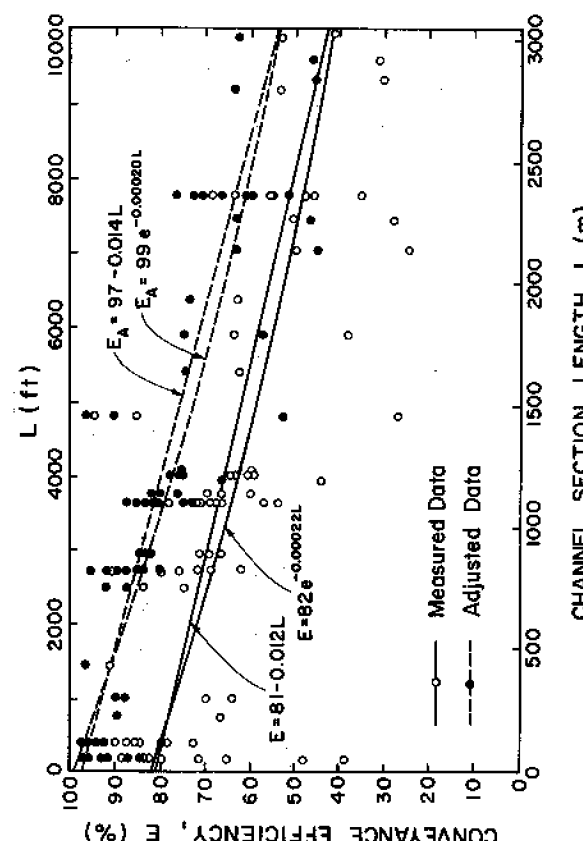
$$\frac{(Q_L - Q_{LO})_M}{R_0} = K_2 S^{-1.013} D_n^{0.824} D_0^{1.57} B^{1.367} \dots \dots \dots (10)$$

in which  $K_2 = 0.604$  when the lengths are expressed in meters and 0.585 when they are given in feet. The  $r^2$  value for this approximation is 0.997. The maximum deviation from the generated data is 14%. The average deviation (residual) is 4%.

In channel sections longer than  $L_M$ , the extra water loss caused by the device can be predicted by Eq. 10, while in shorter channels ( $L < L_M$ ) the device induced loss can be predicted from Eqs. 9 and 10 and Fig. 5 or Eq. 8. These absolute induced losses can be converted to the relative loss rate or device effects factor,  $F$ , with Eq. 7.

**VERIFICATION OF DEVICE EFFECTS**

Although the previously referenced loss data indicate that flow measurement devices affect water loss from earthen channels, quantitatively verifying the developed device effects relationships is difficult because of inaccuracies in flow measurement and variabilities in channel conditions. Flow measurement devices are generally accurate to no more than  $\pm 3\%$  to 5% in the field. This inaccuracy is compounded when the difference between two measurements is used to calculate a loss, especially if the measurements are made in short sections (where device effects are most pronounced) because the absolute loss is smaller. Measurement flow without creating a significant head loss to get comparative baseline loss data is even more difficult and less accurate. Variations in slopes, cross sections, and roughness in existing earthen channels make steady, uniform flow an approximation at best. Wide variations in loss rates along a channel further complicate verification of device effects. Due to these inaccuracies and variability, the device effects relationships can be validated only through statistical analysis of extensive data (including all input parameters). The best data available for this purpose were collected during five watercourse operational loss studies in Pakistan (11). In these studies, inflows to and outflows from five watercourse systems were measured continuously for three weeks with flumes. An example of these data for one watercourse, presented as conveyance efficiencies,  $E$  (outflow/inflow  $\times 100$ ), is shown in Fig. 7. Both linear and exponential regression lines, which assume a constant loss rate and a loss rate proportional to the flow rate, respectively, are shown for the



**FIG. 7.—Conveyance Efficiency versus Distance from Channel Head for One Watercourse Showing Measured Values and Measurements Adjusted for Device Effects. Linear and Exponential Regression Lines are Shown for Both Data Sets**

**TABLE 2.—Operational Loss Study Inflow-Outflow Conveyance Efficiency Regression Equations Fit to Original Data and Data Adjusted for Device Effects**

Watercourse* (1)	Linear regression equation (2)	r <sup>2</sup> (3)
MP 52	$E = 81 - 0.012L$	0.40
MP 52-ADJ	$E_A = 97 - 0.014L$	0.73
MP 6	$E = 99 - 0.012L$	0.27
MP 6-ADJ	$E_A = 101 - 0.011L$	0.33
MP 35	$E = 92 - 0.011L$	0.17
MP 35-ADJ	$E_A = 98 - 0.012L$	0.31
TW 81-R	$E = 91 - 0.018L$	0.19
TW 81-R-ADJ	$E_A = 96 - 0.018L$	0.24
Tik 1	$E = 87 - 0.003L$	0.03
Tik 1-ADJ	$E_A = 92 - 0.004L$	0.10

\*ADJ refers to data adjusted for device effects by Eq. 7.

Note: E expressed as a percentage; and L in m.

data. Both have an intercept value significantly below 100. The data indicate that loss rates increase as section length decreases.

For the particular watercourse shown, the channel slopes average 0.00045 and the loss vs. depth relationship exponent, determined by ponding measurements in selected sections, averaged  $20 \text{ m}^{-1}$  ( $6.1 \text{ ft}^{-1}$ ). The normal flow depth averaged 0.4 m (1.3 ft), and the flumes created an average of 0.08 m (0.25 ft) of head loss in the flow. The device effects analysis predicts for these conditions a maximum loss increase of  $794 \times R_0$  ( $242 \times R_0$ ) where  $R_0$  is the original loss rate in percent per meter (%/ft). The length of the backwater is predicted to be 1,150 m (3,770 ft).

Fig. 7 also shows the conveyance efficiency data after adjusting for the predicted device effects with Eqs. 7 and 8, and the regression lines which best fit the adjusted data. These lines project more nearly through 100% efficiency at the channel head. Thus, adjusting the loss data for device effects eliminated much of the variability of loss rate with channel length.

Similar analyses were made of the data from the other four watercourses. The linear regression equations which best fit the original and adjusted data are given in Table 2. In four of the data sets, the adjustment moved the intercept closer to 100% and reduced loss rate variability. In the fifth data set, the original intercept was close to 100% and the device effect adjustment was slight.

## SUMMARY AND CONCLUSIONS

Because of the head loss caused by flow measurement devices and a strong relationship between loss and depth-of-flow changes, the devices will cause water loss from earthen channels beyond those which normally occur. These effects are especially important in channels with small slopes ( $<0.0006$ ) and a strong loss vs. depth relationship. In these channels, inflow-outflow losses should only be measured in long channel sections ( $>2000 \text{ m}$  ( $6000 \text{ ft}$ )) with devices which create the minimum possible head loss in the flow.

Measurement device effects can be calculated by the developed numerical procedure or approximated with the equations presented so that the effects can be predicted and accounted for. Adjusting measured loss data for the device effects eliminated much of the otherwise unexplainable relationship between loss rates and length of section measured.

## APPENDIX I.—REFERENCES

1. Akram, M., Kemper, W. D., and Sabey, J. D., "Water Levels and Losses and Clearing in Watercourses," *Transactions of the American Society of Agricultural Engineers*, Vol. 24, No. 3, June, 1981, pp. 643-650.
2. Ashraf, M., Kemper, W. D., Chowdhry, M. M., Ahmed, B., and Trout, T., "Review of Water Loss Measurement in Pakistan," *In Improving Irrigation Water Management on Farms*, Annual Technical Report, Colorado State University, Fort Collins, Colo., 1978, pp. 206-229.
3. Brockway, D. E. and Worstell, R. V., "Field Evaluation of Seepage Measurement Methods," *Proceedings, Second Seepage Symposium*, Phoenix, Ariz., Mar. 25-27, 1968, ARS 41-147, pp. 121-127.
4. Chow, V. T., *Open-Channel Hydraulics*, McGraw-Hill Book Co., Inc., New York, N. Y., 1959, pp. 262-265.
5. Early, A. C., Freeman, D. M., and Lowdermilk, M. K., "Consequences of a Farmer's Reactions to Indus Basin Water Management Constraints," *Paper No. 79-5054*, presented at the Summer Meeting of the American Society of Agricultural Engineers, University of Manitoba, Winnipeg, Manitoba, Canada, June, 1979.
6. Hanson, E. G., "The Seepage Problem Defined," *Paper No. 66-728*, presented at the Winter Meeting of the American Society of Agricultural Engineers, Chicago, Ill., Dec. 6-9, 1966.
7. Lowdermilk, M. K., Early, A. C., and Freeman, D. M., "Farm Irrigation Constraints and Farmers' Responses: Comprehensive Field Survey in Pakistan," *Technical Report No. 48*, Water Management Research Project, Colorado State University, Fort Collins, Colo., (6 volumes), 1978.
8. Robinson, A. R., Jr. and Rohwer, C., "Measurement of Canal Seepage," *Transactions, ASCE*, Vol. 122, 1957, pp. 347-363.
9. Skogerboe, G. V., Bennett, R., and Walker, W., "Selection and Installation of Cutoff Flumes for Measuring Irrigation and Drainage Water," *Technical Bulletin No. 120*, Colorado Agricultural Experiment Station, Fort Collins, Colo., 1973.
10. Trout, T. J., "Factors Affecting Losses from Indus Basin Irrigation Channels," thesis presented to Colorado State University (at Fort Collins, Colo.) in 1979, in partial fulfillment of the requirements for the degree of Doctor of Philosophy. Also: *Technical Report No. 50*, Water Management Research Project, Colorado State University, Fort Collins, Colo., 1979.
11. Trout, T. J. and Bowers, S. A., "Operational Evaluation of Village Level Irrigation Conveyance Systems," *Transactions of the American Society of Agricultural Engineers*, Vol. 24, No. 3, June, 1981, pp. 636-642.

## APPENDIX II.—NOTATION

The following symbols are used in this paper:

- A = channel cross-sectional flow area ( $\text{m}^2$ );  
 B = exponential coefficient relating loss to flow depth changes (Eq. 4) ( $\text{m}^{-1}$ );  
 C<sub>1</sub> = empirical coefficient in Eq. 1;  
 C<sub>2</sub> = empirical coefficient in Eq. 1;  
 D = flow depth (m);

- $D_n$  = normal flow depth (m);  
 $D_0$  = amount flow depth is increased by a flow measurement device (m);  
 $E$  = conveyance efficiency ((outflow/inflow)  $\times$  100) (%);  
 $E_A$  = conveyance efficiency adjusted for device effects (%);  
 $F$  = relative water loss in a channel section or device effects factor;  
 $K_1$  = regression intercept of Eq. 9;  
 $K_2$  = regression intercept of Eq. 10;  
 $L$  = length of channel section (m);  
 $L_M$  = length of backwater profile (m);  
 $n$  = Manning's roughness coefficient ( $m^{-1/3} \cdot sec$ );  
 $P$  = wetted perimeter length (m);  
 $Q$  = flow rate (L/sec);  
 $Q_L$  = flow loss (L/sec or %);  
 $Q_{LO}$  = flow loss when  $D = D_n$  (L/sec or %);  
 $R$  = loss rate in a channel (flow loss per unit length) (L/sec/m or %/m);  
 $R_0$  = loss rate in a channel without measurement device installed (L/sec/m or %/m);  
 $S$  = channel slope (m/m); and  
 $T$  = water surface width (m).