SUITABILITY OF SELECTED FLOW EQUATIONS AND VARIATION OF MANNING’S $n$ IN FURROW IRRIGATION

By M. Esfandiari and B. L. Maheshwari

ABSTRACT: Simulation models are becoming valuable tools for design and management of furrow irrigation systems. The Manning equation is used often for describing overland flow in these models. The past studies suggest that the Manning equation is not suitable for describing the flow in border irrigation because the value of Manning’s $n$ varies with the depth of flow. In this study we examine the suitability of the Manning and other four similar flow equations for flow in furrow irrigation and evaluate how Manning’s $n$ varies spatially, temporally, and with flow rate in the furrow. Field tests were monitored for a range of flow rates and two furrow slopes. The Manning and the other equations fitted data satisfactorily. The value of the Manning’s $n$ varied slightly with the variation in flow rate at low flow range, but it became fairly constant with changes in flow rate at high flow range. The Manning equation is considered the best for modeling the overland flow in furrow irrigation among the equations examined in the study because the Manning equation requires only one parameter to be estimated, whereas in the other equations up to four parameters should be estimated.

INTRODUCTION

Flow in furrow irrigation differs from that in open channels and rivers in several ways. The flow rates in furrows are lower, the depth of flow is shallower (<150 mm) and the velocities of flow are small (0.02 to 0.04 m s$^{-1}$). In furrow irrigation, the flow is often a mixture of laminar and turbulent flow, whereas in deep flow conditions such as rivers the flow is more likely to be turbulent. Furrow irrigation models are valuable tools in the design and management of irrigation systems. Advance and recession times of the waterfront and in turn the uniformity of irrigation can be predicted by the models for a given field condition. The hydraulic resistance parameter is one of the key input parameters in the models and therefore its accurate estimation is important for obtaining reliable predictions from the models. Modelers of furrow irrigation have used the Manning equation for describing the velocity of flow in their models (Elliott et al. 1982; W. R. Walker and F. Gichuki, unpublished report, 1985; P. Ross, unpublished notes, 1986; Wallender 1986; Strelkoff 1991). The Manning equation was derived for deep flow conditions such as those in rivers (Maheshwari and McMahon 1992). Studies of Maheshwari and McMahon (1992) indicate that the value of Manning’s $n$ in border irrigation varies with depth of flow and the equation is not suitable for flows in border irrigation. This raises a question whether the equation can be used for modeling furrow irrigation flows that have shallow depth like in border irrigation. However, the flow in furrow irrigation differs from border irrigation such that the flow in the former case is in a small channel and generally there is no vegetative cover in the channel to obstruct the flow.

The following are the main objectives of this study: (1) To investigate the suitability of the Manning and other four similar flow equations for describing flow in furrow irrigation; and (2) to evaluate variation of the Manning’s $n$ with the distance down the furrow, watering number during the season and flow rate used.

FIELD EXPERIMENTS

General

The field experiments were conducted at the Horticulture Farm of the University of Western Sydney, NSW, Australia. The experiments in the study were part of a wider study on the evaluation of furrow irrigation models for southeast Australia. For convenience, the horticulture farm is hereafter referred to as HF. Because experiments at HF comprised of both irrigation and hydraulic resistance tests, the hydraulic resistance tests at HF are called HPH.

Field Setup

The field layout of one of the furrow sets at the experimental site is shown in Fig. 1. The topsoil (up to 0.3 m) at the site is sandy clay loam and the subsoil below it is a clay that has

![Diagram of field setup](http://example.com/diagram.png)

FIG. 1. Plan View Showing General Layout, Water-Level Probe, Inflow, and Outflow Flumes in Furrow No. 3 at HF Site; Furrow No. 8 Also Had Similar Arrangement

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Flow in the flume and stations along the furrow were measured. Depths were recorded. The incremental value for obtaining the desired distances down the furrow. Cross sections of furrows along the length were measured before and after each test. A portable RBC flume designed by Bos et al. (1984) with a throat width of 100 mm was used for measuring flow rates. The depths of flow in the flume and stations along the furrow were measured using water-level probes and a data logger. The depths were recorded every 10 s by the data logger.

Field Measurements

The measurements made for the hydraulic resistance tests included inflow and outflow rates and depth of flow at different distances down the furrow. Cross sections of furrows along the length were measured before and after each test. A portable RBC flume designed by Bos et al. (1984) with a throat width of 100 mm was used for measuring flow rates. The depths of flow in the flume and stations along the furrow were measured using water-level probes and a data logger. The depths were recorded every 10 s by the data logger.

A very low hydraulic conductivity. A total of six furrow sets were constructed for monitoring both irrigation events and hydraulic resistance tests. Each furrow set consists of three furrows with the middle furrow used for monitoring the irrigation events or hydraulic resistance tests (see Fig. 1). Only furrow set nos. 3 and 8 were used for monitoring the hydraulic resistance tests. The length, spacing, and slope of the furrows in the two sets (i.e., nos. 3 and 8) used in the tests are given in Table 1.

Each furrow is divided into six sections (see Fig. 2). Because of a constant infiltration along the furrow after soil became saturated, the flow in the furrow decreased gradually along the length. By dividing a furrow into sections and measuring flow depths along the furrow, we increased the number of observations per watering for analysis. The field was planted with barley and a total of six waterings for the hydraulic resistance tests, three in each furrow set, were monitored.

For monitoring the tests, flow rate is measured in the furrow by installing two flumes, one at the upstream and the other at the downstream ends of the furrow and the depth of flow by placing water-level probes along the length of the furrow. In each furrow set, water was applied in all three furrows simultaneously. This was done to prevent lateral seepage and to provide infiltration conditions similar to a typical furrow irrigation practice. Water was supplied into the furrows by an adjustable gated pipe.

A total of eight flow rates in the range of 0.13 and 3.5 L s⁻¹ were used during each watering. Watering began with a low flow rate (e.g., 0.13 L s⁻¹). It was observed that outflow from the furrow became constant within 10 min after the water front has reached the furrow end, but the flow was continued for approximately 30 min to make sure that the flow depths in the entire furrow have become stable. These flow depths, recorded by water-level probes along the furrow, provided the required depth values. The flow rate into the furrow was then increased to a next value and flow depths at stable flow conditions were recorded again. The increase in flow rate was repeated until all other flow rates and corresponding flow depths were recorded. The incremental value for obtaining different flow rates used during a watering varied between 0.2 and 0.8 L s⁻¹.

Field Measurements

The measurements made for the hydraulic resistance tests included inflow and outflow rates and depth of flow at different distances down the furrow. Cross sections of furrows along the length were measured before and after each test. A portable RBC flume designed by Bos et al. (1984) with a throat width of 100 mm was used for measuring flow rates. The depths of flow in the flume and stations along the furrow were measured using water-level probes and a data logger. The depths were recorded every 10 s by the data logger.

Calculation of Flow Rate at Stations along Furrows

As mentioned earlier, the subsoil at the experimental site is clay having very low hydraulic conductivity. The subsoil con-
controlled the long-term infiltration at the site. It was observed that outflow from the furrow became constant within 10 min after the waterfront reached the furrow end. This provided condition for a steady, gradually varied flow in the furrow. The flow rate at any stations along the furrow was calculated using the following equation:

$$Q_i = Q_o - (Q_i - Q_o) \times \frac{X_i}{X_L}$$  \hspace{1cm} (1)

where \( Q_i \) = flow rate at the station (m³ s⁻¹); \( Q_o \) = inflow into the furrow (m³ s⁻¹); \( Q_s \) = outflow from the furrow (m³ s⁻¹); \( L \) = the length of furrow (m); and \( X \) = distance of the station from the upstream end of the furrow (m).

### Adjustment of Bed Elevation and Depth of Flow at Each Station

Because of irregularities in furrow slope it was observed that water lies stagnant on the surface in depressions around the location of the water-level probe along the furrow. The depths of stagnant water at different stations were measured manually after each watering. For a given station, there was negligible change in the depths of stagnant water from one watering to the next in the furrow. The measured depth of stagnant water was used to adjust the bed elevation and the depth of flow at each station as follows:

$$E_i = E_{iu} + d_i$$  \hspace{1cm} (2)

and

$$Y_i = Y_{iu} - d_i$$  \hspace{1cm} (3)

where \( E_i \) = adjusted bed elevation at station \( i \) (m); \( E_{iu} \) = measured bed elevation from surveying at station \( i \) (m); \( d_i \) = measured depth of stagnant water at station \( i \) (m); \( Y_i \) = adjusted depth of flow at station \( i \) (m); \( Y_{iu} \) = measured flow depth from water-level probe at station \( i \) (m).

Also, the measured cross section of furrow was adjusted using the adjusted bed elevation at each station. The adjusted cross section was used to calculate the different hydraulic parameters such as cross-sectional area of flow in furrows.

### Calculation of Slope of Energy Line (Sₜ)

Consider a steady, gradually varied flow along the furrow as shown in Fig. 4. The Bernoulli's equation between stations 1 and 3 can be stated as follows:

$$\Delta E + Y_1 + \frac{V_1^2}{2g} = Y_3 + \frac{V_3^2}{2g} + S_τΔL$$  \hspace{1cm} (4)

Eq. (4) can be rearranged for \( S_τ \), as follows:

$$S_τ = \frac{\Delta E}{ΔL} + \frac{Y_1 - Y_3}{ΔL} + \frac{V_1^2 - V_3^2}{2gΔL}$$  \hspace{1cm} (5)

where \( S_τ \) = slope of energy line between stations 1 and 3; \( ΔE \) = adjusted bed elevation difference (m) between stations 1 and 3; \( ΔL \) = distance (m) between stations 1 and 3; \( Y_1 \) and \( Y_3 \) = adjusted depth of water (m) at stations 1 and 3, respectively; \( V_1 \) and \( V_3 \) = flow velocity (m s⁻¹) at stations 1 and 3, respectively; and \( E_i \) and \( E_t \) = adjusted bed elevation (m) at stations 1 and 3, respectively.

All parameters in (5), except \( S_τ \), can be measured or known. Therefore, the value of \( S_τ \) can be calculated between stations 1 and 3 using (5). The value of \( S_τ \) calculated using (5), based on stations 1 and 3, provides value of \( S_τ \) for the middle station (i.e., station 2). Similarly, \( S_τ \) based on stations 2 and 4 will provide \( S_τ \) for station 3.

### Selected Flow Equations

The Manning equation and four variations of the Manning equation were used. The Manning equation is expressed as follows:

$$Q = \frac{A}{n} R^{n/3} S_τ^{5/3}$$  \hspace{1cm} (7)

Eq. (7) can be rewritten as

$$Q = KAR^{n/3} S_τ^{5/3}$$  \hspace{1cm} (8)

The other four equations are

$$Q = k_1AR^{1/3} S_τ^{5/3}$$  \hspace{1cm} (9)

$$Q = k_2AR^{2/3} S_τ^{5/3}$$  \hspace{1cm} (10)

$$Q = k_3AR^{3/3} S_τ^{5/3}$$  \hspace{1cm} (11)

$$Q = k_4AR^{4/3} S_τ^{5/3}$$  \hspace{1cm} (12)

where \( Q \) = flow rate (m³ s⁻¹); \( n \) = Manning coefficient; \( A \) = cross-sectional area of flow (m²); \( K \) = 1/3; \( R \) = hydraulic radius (m); \( P \) = wetted perimeter (m); \( S_τ \) = slope of energy line; \( β_1 \) and \( β_2 \) = exponents for \( S_τ \) in the equations; \( k_1 \), \( k_2 \), \( k_3 \), and \( k_4 \) = coefficients in the equations; and \( α_1 \), \( α_2 \), \( α_3 \), \( α_4 \), and \( α_5 \) = exponents for furrow geometry parameters in the equations.

Eqs. (9) and (10) are the same as the Manning equation except the exponent of hydraulic radius in (9) and the exponents of hydraulic radius and slope of energy line in (10) are allowed to vary. Eqs. (11) and (12) also are similar to (9) and (10), respectively, but the hydraulic radius in the equation is replaced by the wetted perimeter.

### Fitting Flow Equations

For fitting the flow equations, a nonlinear optimization method (Maheshwari and McMahon 1992) that uses a pattern search technique (Monro, 1971) was used. In this method, the parameters \( K \), \( k_1 \), \( k_2 \), \( k_3 \), \( k_4 \), \( α_1 \), \( α_2 \), \( α_3 \), \( α_4 \), \( α_5 \), \( β_1 \), and \( β_2 \) in the flow equations are assigned some initial values and these values are then changed during each iteration until the difference between the observed and the predicted "Q" values become negligible. The objective function used for the optimization method was as follows:

$$ΔQ = \sum_{i=1}^{N} (Q_{oi} - Q_{pi})^2$$  \hspace{1cm} (13)

where \( ΔQ \) = value of objective function (m³ s⁻¹); \( N \) = number of observations in test; \( Q_{oi} \) = observed value of ith \( Q \) (m³ s⁻¹); and \( Q_{pi} \) = the predicted value of ith \( Q \) (m³ s⁻¹).

For evaluating whether the equation fits, the values of \( R^2 \) and standard deviation (σ) were calculated for each test.
Validation of Flow Equations

The validation of different flow equations for estimating flow rate in furrow irrigation has been done by comparing the calculated flow rate with that observed in the field. The observed values of flow rates in furrow \( Q \), and that calculated using the selected flow equations \( Q_c \) can be compared and analyzed to further aid in the evaluation of different flow equations for estimating flow rate in furrow irrigation. Here, a linear regression analysis of observed and calculated flow rates was used to find the average pattern of variation of data. The form of regression equation selected is

\[
Q_c = \lambda Q_o
\]

where \( Q_c \) = predicted value of \( Q \) from regression of \( Q_c \) on \( Q_o \) (m³ s⁻¹); and \( \lambda = \) coefficient.

The goodness of fit of the foregoing equation to data is determined usually by calculating the coefficient of determination \( R^2 \) and the standard error of estimate (\( \sigma \)). When \( R^2 \) fits the data satisfactorily, a value of \( \lambda \) close to unity means unbiased prediction, \( \lambda < 1 \) indicates underprediction, and \( \lambda > 1 \) means overprediction. The average absolute error \( E_{av} \) in percentage was computed for each flow equation to measure the goodness of fit and is given as

\[
E_{av} = \left( \frac{100}{N} \sum_{i=1}^{N} \left( \frac{Q_{cal} - Q_{obs}}{Q_{obs}} \right) \right)
\]

RESULTS AND ANALYSIS

Fitting Flow Equations

The data obtained from the hydraulic resistance tests monitored in this study were used to examine the suitability of the Manning and the other flow equations for modeling the overland flow in furrow irrigation and to estimate the values of the parameters \( K (K = 1/n, \text{where } n \text{ is the Manning coefficient}) \) in the Manning and \( k_1, k_2, k_3, k_4, \alpha_1, \alpha_2, \beta_1, \alpha_3, \alpha_4, \beta_1, \text{ and } \beta_2 \) in the other flow equations. The results of fitting of the various flow equations using the field data for each watering within each furrow (level 1) are given in Table 2.

As shown in Table 2, the Manning and the other flow equations fitted satisfactorily \( (R^2 > 0.86 \text{ and } \sigma < 0.36 \text{ L/s}) \) for level 1 data sets. This shows the Manning and the other flow equations are suitable for describing overland flows in furrow irrigation on bare soils.

As shown in Table 2, the value of \( K \) parameter in the Manning equation decreased from watering no. 1 to no. 3 in each furrow. This means the value of the Manning's \( n \) increased gradually from watering no. 1 to no. 3 for each furrow. This probably is caused by an increase in surface roughness caused by soil erosion in the furrow during subsequent watering.

The results of fitting of the different flow equations using data of three waterings combined for each furrow (level 2) are given in Table 3. As shown in Table 3, the flow equations also fitted satisfactorily \( (R^2 > 0.88 \text{ and } \sigma < 0.30 \text{ L/s}) \) for level 2 data sets. The value of the parameter \( K \) in the Manning equation for furrow no. 3 (i.e., 62) is higher than in furrow no. 8 (i.e., 57). This means the Manning's \( n \) for furrow no. 3 (i.e., 0.016) is smaller than Manning's \( n \) for furrow no. 8 (i.e., 0.0175). This can be explained by more erosion, which occurred in furrow no. 8 because of its steeper slope.

The results of fitting the different flow equations using data of all waterings (i.e., data set HFH-all) of both furrows combined (level 3) are given in Table 4. As shown in Table 4, the flow equations again fitted the field data satisfactorily, al-
The validation of flow equations at all levels in general fitted the field data satisfactorily in all cases. The Manning equation is superior to the other flow equations, mainly because the equation requires only one parameter (i.e., $K$) to be estimated, whereas in other equations up to four parameters should be estimated.

### Validation of Flow Equations

As mentioned earlier, half of the field data in each data set were used to evaluate the performance of the different flow equations. The performance of the different flow equations for predicting flow rates during the hydraulic resistance tests monitored in this study was quantified by calculating $R^2$, $\sigma$, $N$, and $E_\text{av}$ for data sets at all three levels (see Tables 5–7).

As shown in Table 5 (level 1), the Manning equation and (9) and (10) predicted flow rates with a relatively high accuracy ($R^2 = 0.91$ and $E_\text{av} < 15.4\%$) in comparison with other flow equations. The Manning equation is the best ($R^2 = 0.91$ and $E_\text{av} = 15\%$) for the prediction of flow rate among the equations considered at this level 1. As shown in Table 6 (level 2), all the flow equations except (11) predicted flow rate with the same accuracy. Eqs. (10) and (12) appeared to be best for prediction of flow rate at level 2. As shown in Table 7 (level 3), the Manning equation and (9) and (11) predicted flow rates with a relatively high accuracy ($R^2 = 0.88$ and $E_\text{av} < 18.3\%$) in comparison with other equations. The Manning equation is the best ($R^2 = 0.88$ and $E_\text{av} = 18.3\%$) for the prediction of flow rate among the equations considered at level 3.

In general, the validation of flow equation at all levels indicates that the Manning equation is superior to the other equations for prediction of flow rate for the hydraulic resistance tests monitored in the present study.

### Table 3. Optimized Values of Parameters for Various Flow Equations at HF Site for All Waterings in Both Furrows Combined (Level 3)

<table>
<thead>
<tr>
<th>Equation and parameter values</th>
<th>$R^2$</th>
<th>$\sigma$</th>
<th>$N$</th>
<th>$K$</th>
<th>$k_1$</th>
<th>$\alpha_1$</th>
<th>$k_2$</th>
<th>$\alpha_2$</th>
<th>$\beta_1$</th>
<th>$k_3$</th>
<th>$\alpha_3$</th>
<th>$k_4$</th>
<th>$\alpha_4$</th>
<th>$\beta_2$</th>
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<tbody>
<tr>
<td>$Q = kARa^2g_{0.5}$</td>
<td>0.92</td>
<td>0.27</td>
<td>72</td>
<td>62.0</td>
<td>33.3</td>
<td>0.48</td>
<td>25.8</td>
<td>0.44</td>
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<td>$Q = kARa^2g_{0.5}$</td>
<td>0.90</td>
<td>0.28</td>
<td>72</td>
<td>31.5</td>
<td>0.43</td>
<td>0.51</td>
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<tr>
<td>$Q = kARa^2g_{0.5}$</td>
<td>0.92</td>
<td>0.27</td>
<td>72</td>
<td>4.7</td>
<td>0.31</td>
<td>0.31</td>
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### Table 4. Optimized Values of Parameters for Various Flow Equations at HF Site for All Waterings in Both Furrows Combined (Level 3)

<table>
<thead>
<tr>
<th>Equation and parameter values</th>
<th>$R^2$</th>
<th>$\sigma$</th>
<th>$N$</th>
<th>$K$</th>
<th>$k_1$</th>
<th>$\alpha_1$</th>
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<tr>
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<td>72</td>
<td>60.8</td>
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<td>$Q = kARa^2g_{0.5}$</td>
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<td>72</td>
<td>38.5</td>
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<tr>
<td>$Q = kARa^2g_{0.5}$</td>
<td>0.92</td>
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### Table 5. Values of $\lambda$, $R^2$, $\sigma$, and $E_\text{av}$ for Various Flow Equations for Level 1 Data Sets

<table>
<thead>
<tr>
<th>Equation</th>
<th>$\lambda$</th>
<th>$R^2$</th>
<th>$\sigma$</th>
<th>$E_\text{av}$</th>
<th>$N$</th>
</tr>
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<tr>
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<td>0.91</td>
<td>0.25</td>
<td>15.0</td>
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<tr>
<td>$Q = kARa^2g_{0.5}$</td>
<td>0.94</td>
<td>0.91</td>
<td>0.26</td>
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<td>144</td>
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<tr>
<td>$Q = kARa^2g_{0.5}$</td>
<td>0.96</td>
<td>0.91</td>
<td>0.24</td>
<td>15.2</td>
<td>144</td>
</tr>
<tr>
<td>$Q = kARa^2g_{0.5}$</td>
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<td>0.88</td>
<td>0.28</td>
<td>18.0</td>
<td>144</td>
</tr>
<tr>
<td>$Q = kARa^2g_{0.5}$</td>
<td>0.96</td>
<td>0.88</td>
<td>0.28</td>
<td>23.5</td>
<td>144</td>
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### Table 6. Values of $\lambda$, $R^2$, $\sigma$, and $E_\text{av}$ for Various Flow Equations for Level 2 Data Sets

<table>
<thead>
<tr>
<th>Equation</th>
<th>$\lambda$</th>
<th>$R^2$</th>
<th>$\sigma$</th>
<th>$E_\text{av}$</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q = kARa^2g_{0.5}$</td>
<td>0.93</td>
<td>0.87</td>
<td>0.34</td>
<td>17.9</td>
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<tr>
<td>$Q = kARa^2g_{0.5}$</td>
<td>0.92</td>
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<tr>
<td>$Q = kARa^2g_{0.5}$</td>
<td>0.95</td>
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<td>0.94</td>
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<td>$Q = kARa^2g_{0.5}$</td>
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<td>0.87</td>
<td>0.30</td>
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</table>

### Table 7. Values of $\lambda$, $R^2$, $\sigma$, and $E_\text{av}$ for Various Flow Equations for Level 3 Data Sets

<table>
<thead>
<tr>
<th>Equation</th>
<th>$\lambda$</th>
<th>$R^2$</th>
<th>$\sigma$</th>
<th>$E_\text{av}$</th>
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<tbody>
<tr>
<td>$Q = kARa^2g_{0.5}$</td>
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<td>0.88</td>
<td>0.32</td>
<td>18.3</td>
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<td>0.88</td>
<td>0.31</td>
<td>18.5</td>
<td>144</td>
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<tr>
<td>$Q = kARa^2g_{0.5}$</td>
<td>0.97</td>
<td>0.87</td>
<td>0.31</td>
<td>22.5</td>
<td>144</td>
</tr>
<tr>
<td>$Q = kARa^2g_{0.5}$</td>
<td>0.95</td>
<td>0.86</td>
<td>0.31</td>
<td>22.8</td>
<td>144</td>
</tr>
</tbody>
</table>

TABLE 8. Values of $F_{\text{calculated}}$ and $F_{\text{critical}}$ for Data Sets at Different Levels of Analysis at 95% Confidence Level

<table>
<thead>
<tr>
<th>Level (1)</th>
<th>$F_{\text{calculated}}$ (2)</th>
<th>$F_{\text{critical}}$ (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.19</td>
<td>3.23</td>
</tr>
<tr>
<td>2</td>
<td>0.13</td>
<td>3.23</td>
</tr>
<tr>
<td>3</td>
<td>0.21</td>
<td>3.23</td>
</tr>
</tbody>
</table>

Statistical Differences in Flow Prediction

To examine whether there is a significant difference between the mean of predicted flow rates by the different flow equations, statistical analysis using the $F$-test was carried out at 95% confidence level. As shown in Table 8, the values of $F_{\text{calculated}}$ are much lower than the values of $F_{\text{critical}}$ in all cases. This means there is no significant difference between the mean of predicted flow rates by the different flow equations.

Variation of Manning’s $n$

The values of the Manning’s $n$ for different tests at each section were calculated using the Manning equation and the trends of variation of the Manning’s $n$ with flow rate during each watering at different sections along the furrows are shown in Fig. 5. As shown in Fig. 5, Manning’s $n$ value changed slightly with changes in flow rate at low flow range (i.e., flows $<0.70$ L s$^{-1}$), but it became fairly constant with changes in flow rate at the high flow range (i.e., flows $>0.70$ L s$^{-1}$). The variation in Manning’s $n$ at low flows may be related to rapid changes in wetted perimeter and consequently the surface area of soil. Also, measurement errors in cross-sectional area of furrow, flow depth, and flow rate at low flow may be relatively high and could contribute to variation of Manning’s $n$. In high flow range, Manning’s $n$ does not change much and could be explained by the fact that resistance to flow in furrow irrigation is caused by soil surface roughness, which does not change with changes in the flow depth. This is in contrast to border irrigation in which Manning’s $n$ varies with depth of flow because of presence of vegetation in the flow path (Maheshwari and McMahon 1992).

As shown in Fig. 5, the value of the Manning’s $n$ is not the same for different sections during each watering. This may be related to the variation of the soil surface roughness within

![Data set: HPH1](image)

![Data set: HPH2](image)

![Data set: HPH3](image)

![Data set: HPH4](image)

**FIG. 5. Variation of Manning’s $n$ with Flow Rate at Various Sections during Different Waterings**

94 / JOURNAL OF IRRIGATION AND DRAINAGE ENGINEERING / MARCH/APRIL 1998
different sections. The values of Manning's $n$ increased gradually from watering no. 1 to no. 3 for each furrow. This probably is caused by increased surface roughness caused by soil erosion in the furrow during subsequent waterings.

Trout (1992) tried to fit linear regression equations between Manning's $n$ and flow velocity and Manning's $n$ and hydraulic radius, but the correlation was poor. The present study suggests that Manning's $n$, except for a low flow range, did not vary much with the variation of flow velocity. Hydraulic resistance in overland flow is a result of complex interactions between soil surface and flowing water. It is not correct to develop correlations between Manning's $n$ and velocity of flow or hydraulic radius because these variables are not related in the physical sense. If the field data show a systematic variation in Manning's $n$ with velocity or hydraulic radius, it should be recognized as a secondary effect (Maheshwari 1992). Therefore, any attempt to develop a relationship between Manning's $n$ with the velocity or the hydraulic radius will have a poor correlation.

CONCLUSIONS

Based on the analysis of field data in the present study, it is concluded that the Manning and the other four equations are suitable for describing the overland flow in furrow irrigation models. For a given watering, Manning's $n$ does not change much for flows greater than 0.7 L s$^{-1}$ in the furrows. The value of Manning's $n$ tends to increase with each watering and the increase is higher in steeper furrow because of erosion in the furrows. The Manning equation is considered superior to the other equations because in the Manning equation only one parameter should be estimated whereas in other equations up to four parameters need to be estimated.

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APPENDIX I. REFERENCES


APPENDIX II. NOTATION

The following symbols are used in this paper:

- $A$ = cross-sectional area of flow (m$^2$);
- $d_i$ = measured depth of stagnant water at station $i$ (m);
- $E_i$ and $E_3$ = adjusted bed elevation (m) at stations 1 and 3, respectively;
- $E_m$ = average absolute error (%);
- $E_i$ = adjusted bed elevation at station $i$ (m);
- $E_{m}$ = measured bed elevation from surveying at station $i$ (m);
- $K = 1/n$;
- $k_i, k_2, k_3$, and $k_4$ = coefficients in the equations;
- $L$ = length of furrow (m);
- $N$ = number of observations in test;
- $n$ = Manning coefficient;
- $P$ = wetted perimeter (m);
- $Q$ = flow rate (m$^3$ s$^{-1}$);
- $Q_i$ = inflow into the furrow (m$^3$ s$^{-1}$);
- $Q_o$ = outflow from the furrow (m$^3$ s$^{-1}$);
- $Q_{av}$ = observed value of ith $Q$ (m$^3$ s$^{-1}$);
- $Q_{av}$ = the predicted value of ith $Q$ (m$^3$ s$^{-1}$);
- $Q_{av}$ = flow rate at the station (m$^3$ s$^{-1}$);
- $Q_{p}$ = predicted value of $Q$, from regression of $Q_i$ on $Q_o$ (m$^3$ s$^{-1}$);
- $R$ = hydraulic radius (m);
- $R^2$ = coefficient of determination;
- $S_i$ = slope of energy line between stations 1 and 3 (mm$^{-1}$);
- $S_i$ = slope of energy line between stations 1 and 3 (mm$^{-1}$);
- $S_i$ = distance of the station from the upstream end of furrow (m);
- $Y_i$ and $Y_3$ = flow velocity (m$^3$ s$^{-1}$) at stations 1 and 3, respectively;
- $X = \Delta E$ = adjusted bed elevation difference (m) between stations 1 and 3;
- $Y_{mi}$ = measured flow depth from water-level probe at station $i$ (m);
- $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$, and $\alpha_6$ = exponents for furrow geometry parameters in the different flow equations;
- $\beta_i$ and $\beta_3$ = exponents for $S_i$ in the flow equations;
- $\Delta L$ = distance (m) between stations 1 and 3;
- $\Delta Q$ = value of objective function (m$^3$ s$^{-1}$);
- $\lambda$ = coefficient; and
- $\sigma$ = standard error of estimate (L s$^{-1}$).