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Development of the revised USDA–NRCS intake families for surface irrigation

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ABSTRACT

In the absence of localized field data the US Department of Agriculture–Natural Resources and Conservation Service (USDA–NRCS) intake families have often provided sufficient information for preliminary design, evaluation, or management of surface irrigation systems. However, to more fully utilize advances in procedures for field data collection and analysis as well as the software to automate the hydraulic computations, it has become necessary to revise these intake families. This paper is presented to facilitate the dissemination of these results to the larger international audience as well as provide a more detailed explanation of the protocols used in developing the revised families. A selective comparison is made to illustrate the differences between the original and new curves.

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1. Introduction

In the 1950s, the Soil Conservation Service (SCS)[1] of the US Department of Agriculture (USDA) began a concerted effort to develop general intake relationships to support surface irrigation assessments and designs when field measurements were unavailable. The results of these efforts were two sections of the USDA–Natural Resources and Conservation Service (NRCS) "National Engineering Handbook" (USDA–NRCS, 1974; USDA–NRCS, 1984). Both of these references have been distributed and used worldwide. Of particular importance were the "intake families" first presented in the border irrigation chapter (USDA–NRCS, 1974) and modified for furrows in USDA–NRCS (1984).

Both chapters were consolidated and revised in 2004 and are now available from the NRCS as part 623, chapter four, Surface Irrigation (USDA–NRCS, 2005). One of the major changes in the revised chapter concerned the definition and application of the intake family concept. Since the intake families developed previously are widely known, the writers believe a discussion of the revisions in an international journal is both important and relevant. This paper therefore summarizes the procedures used in the original development as well as the procedures and rationale for the new families. The revised intake families are presented in their metric unit form. And, since an important rationale for the revision was the changes in how infiltration has been represented in evaluation and design over the last half-century, this paper also reviews the concepts of infiltration now widely used in surface irrigation analyses in the US.

2. Infiltration for surface irrigation evaluation and design

Infiltration is perhaps the most crucial process affecting surface irrigation uniformity and efficiency as it is the

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[1] The USDA renamed the Soil Conservation Service the "Natural Resources and Conservation Service" (NRCS) in 1994.

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mechanism that transfers and distributes water from the surface to the soil profile. It is essential to gage or predict the rate of infiltration in order to estimate the amount of water entering the soil and its distribution. Infiltration also affects both the advance and recession processes, and thus is important in estimating the optimal discharge that should be directed to the field.

The infiltration process depends on the physical, chemical, and biological properties of the soil, particularly the surface; the initial distribution of water in the soil prior to irrigation; the movement of water over the surface; and the depth of water on the surface. These properties and conditions vary over a field and collectively cause infiltration itself to exhibit large variation at the field scale. Infiltration is difficult to characterize on a field scale because of the large number of measurements generally necessary.

In the engineering evaluation and design of surface irrigation systems, it has been useful to approximate the infiltration process with empirical functions. The word "intake" is often used to describe infiltration when the geometry of the surface is considered.

One of the simplest and most commonly used approximations for infiltration has been the Kostiakov equation which can be written in general terms for furrow irrigation as:

$$Z = K\tau^{a} \tag{1}$$

in which Z is the cumulative volume of infiltration per unit length, m^3/m. The coefficient K has units of $m^3/m/min^a$ while a is dimensionless. The "intake opportunity time", τ, has units of minutes. Both K and τ can be express in a time frame of hours if desired.

In a border or basin environment where the infiltration is one-dimensional, Eq. (1) can be expressed as:

$$z = k\tau^{a} \tag{2}$$

where z is the cumulative depth of infiltration, m; the coefficient k has units of m/min^a; and a is dimensionless as before.

When the duration of the water application is relatively short, such as in some border and basin systems, the intake rate derived from Eq. (2), $I = \partial z/\partial\tau$, will not significantly underestimate infiltration at the end of irrigation. However, this is not an adequate assumption when the intake opportunity time exceeds 3–4 h, a situation commonly encountered in furrow irrigation and irrigation of large borders or basins. Thus, a more generally applicable relation is the Kostiakov–Lewis equation which adds a term for final or "basic" intake rate, F_0 in $m^3/m/min$ (furrows) or f_0 m/min (borders and basins). The Kostiakov–Lewis function for furrows is therefore:

$$Z = K\tau^{a} + F_0\tau \tag{3}$$

and for borders and basins is:

$$z = k\tau^{a} + f_0\tau \tag{4}$$

It should be noted, K and k will have different values in Eqs. (1) and (2) or in Eqs. (3) and (4) due to differences in the wetted perimeter through which infiltration occurs. It is often necessary to assume that the exponent, a, has the same value for both furrow and border/basin irrigations in order to convert one set of functions to the other.

The cumulative intake in furrow can be expressed as an equivalent depth by:

$$z = \frac{Z}{w} \tag{5}$$

where w is the distance between wetted furrows, m.

It is generally most convenient to express the amount of water necessary to refill the root zone as a depth, z_{req}, m, and then determine the corresponding required furrow intake Z_{req} in m^3/m using Eq. (5). One note of caution – Eq. (5) does not imply that $k = K/w$ nor that $f_0 = F_0/w$. This conversion will be discussed subsequently.

Since surface irrigation is often applied to the fine or medium textured soils and some of these tend to crack, Eqs. (3) and (4) can be extended to include a combined term for cracking and depression storage, c, C:

$$z = k\tau^{a} + f_0\tau + c \tag{6}$$

$$Z = K\tau^{a} + F_0\tau + C \tag{7}$$

The units of c and C are the same as z and Z, respectively but to date there are no general recommendations for values of these terms.

3. Evolution of the original USDA–NRCS intake family concept

When the SCS began a concerted effort to develop general intake relationships to support surface irrigation their intention was to determine coefficients for Eqs. (1)–(4) for common soil types and irrigated conditions. An extensive field effort involving about 1670 individual ring infiltrometer tests were made in grass and alfalfa fields in the US states of Colorado, Wyoming, North Dakota, South Dakota, and Nebraska. There were generally five tests at each site that were subsequently averaged to yield 334 individual measurements. Approximately, 75% of the data were taken in recently irrigated fields.

These ring infiltrometer data were evaluated in several ways using regression. One of the first concepts explored was that of the "basic intake rate" simply being defined as, "*that rate when the change of the rate per hour was one-tenth of its value in inches per hour*." In assuming initially that intake could be represented by Eq. (2), the definition of the "basic intake rate", I_b, was then,

$$I_b = \frac{\partial z}{\partial\tau}\bigg\| \quad \text{when} \quad \frac{\partial^2 z}{\partial\tau^2} = \text{abs}\left(0.10\frac{\partial z}{\partial\tau}\right) \tag{8}$$

which occurs when:

$$\tau = -600(a-1) \tag{9}$$

The basic intake rate thus defined was extracted from the ring infiltrometer data, fitted to Eq. (2), and then grouped into 10 "data layers" represented by averages of all the tests within the layer. The times to infiltrate 1, 2, 3, 4, and 6 in. were interpolated from each field measurement with the results being again averaged over the layer as shown in Table 1.

The original analyses began with the Philip equation (Philip, 1957) since it was thought to yield the best fit of

Table 1 – Layered SCS ring infiltrometer data

Range of I_b (mm/h)	Number of sites	Average					
		I_b (mm/h)	τ_{25} (min)	τ_{51} (min)	τ_{76} (min)	τ_{102} (min)	τ_{152} (min)
Under 2.5	7	2.13	262.0	1146.0	2913.0	5770.0	15600.0
2.8–5.1	21	3.58	136.0	545.0	1288.0	2407.0	6002.0
5.3–10.2	35	7.39	65.1	209.0	439.0	731.0	1510.0
10.4–17.8	49	13.77	40.5	119.0	223.0	344.0	626.0
18–31.8	80	25.91	22.0	64.8	118.0	176.0	313.0
32–45.7	54	37.85	12.9	39.5	75.1	119.0	239.0
46–61	23	54.86	11.4	32.1	53.9	78.5	132.0
61.2–86.4	29	73.41	7.9	22.5	40.2	59.6	101.0
86.6–121.9	18	99.82	6.4	17.5	30.6	42.6	73.2
Over 122	18	145.03	4.3	11.1	21.2	30.7	51.3
Total	334						

the data in Table 1. The expression of the Philip equation is:

$$z = S\tau^{0.5} + A\tau \tag{10}$$

in which S is the soil "sorptivity" in mm/min$^{0.5}$ and A is the soil "transmissivity" in mm/min. The resulting fit with the layered ring data produced the following relations:

$$S = 1.481 \times I_b^{0.352} \tag{11}$$

and

$$A = 0.01266 \times I_b - 0.0775, \quad A \geq 0 \tag{12}$$

The concept of an "intake family" derived from the next step. Discrete values of I_b were selected ranging from 0.55 to 100 mm/h and values of S and A were then computed for each value. The observation that A would be negative for some of the high clay content soils led to the idea that perhaps the exponent should vary from its 0.5 value in Eq. (10). Since Eq. (2) was used to define I_b, an analysis was made to determine a revised A value based on varying exponents. It was further concluded that the $A\tau$ term is nearly constant so an extended form of Eq. (2) was selected for final use. This equation is a special case of Eq. (6) with c being constant for all curves in the intake families:

$$z = k\tau^a + c \tag{13}$$

It is interesting that rather than repeating the sequence of the development with Eq. (13) as the basis, the intake family analyses continued from relations already developed from Eqs. (11) and (12) at the discrete "family" values. Eqs. (10)–(12) were then used to compute values of τ for three values of $z - 25$, 76, and 229 mm. Values of k, a, and c were then solved simultaneously from the three points and became the intake family values in use in the US from about 1960 to the present.

3.1. *Modifications for furrow irrigation*

Throughout the 1950s and 1960s SCS personnel also wrestled with the question of how to represent infiltration in furrow irrigation. Field data were sparse, but there were some data which suggested that intake could be related to wetted perimeter. There was also some understanding that infiltration from the furrow sides was occurring at different rates than from the furrow bottom.

The methodology for developing intake relationships from advance, recession, and inflow–outflow was not well understood. Nevertheless, SCS personnel were making field measurements and attempting to determine intake parameters. By the late 1960s these analyses generally assumed infiltration was proportional to wetted perimeter. Furrow irrigation intake was expressed as:

$$z = (k\tau^a + c)\left(\frac{WP}{w}\right) \tag{14}$$

in which WP is the furrow wetted perimeter in m and w is the irrigated furrow spacing in m. The WP/w adjustment was limited to a value no greater than 1.0.

A substantial effort was made to express the wetted perimeter as a function of flow, Manning n, furrow slope, and furrow shape. Values of Manning n were typically 0.03 or 0.04 and the furrow shape was generally represented as trapezoidal. The concept of extrapolating basic intake rates derived from cylinder infiltrometer measurements to furrow conditions was abandoned. Instead, a fairly large number of values of wetted perimeter were computed using trapezoidal shapes ranging from a 6 cm bottom width and 1:1 side slopes to 15 cm bottom widths with 2:1 side slopes. Values of flow, slope, and Manning n were included in the analysis. The data were then simulated by the following relation:

$$WP = 26.472\left(\frac{Qn}{\sqrt{S}}\right)^{0.4247} + 22.744 \tag{15}$$

where WP is the wetted perimeter in cm, Q is the flow in lps, S is the furrow slope, and n is the Manning n. Eq. (15) then was used to adjust the intake families as shown in Eq. (14).

The differences between lateral and vertical infiltration were introduced by adjusting the constant in Eq. (15). The basis of this adjustment is described as:

> "To account for both vertical intake, which is influenced by gravitational forces, and horizontal intake, which is influenced by suction forces, the wetted perimeter is increased by an empirical constant of 0.7 (21.336 cm). This factor is an average value derived from studies that

> indicate that horizontal intake is a function of the 0.4 power of intake opportunity time.''

3.2. *Rationale for revising the intake families*

The original SCS intake families, based on Eq. (13) have provided users with a starting point in the design and evaluation of surface irrigation systems. Over the years, however, several weaknesses have been evident. First, only about 75% of the original readings were on irrigated fields, and those that were irrigated were dominated by closely spaced perennial crops, either grass or alfalfa. Thus, they did not represent the tilled conditions of irrigated agriculture, particularly the first irrigation following a tillage operation. Second, the circular procedure based on I_b that was used to formulate the coefficients and exponent of Eq. (13) yield unusually high values of the a exponent – values rarely seen in surface irrigation evaluations conducted since 1974. Third, the constant value of c in Eq. (13) of about 7 mm was based on a very simplistic analysis. Data collected since show the value of this term to be time dependent and to vary with soil type. Thus, the Kostiakov–Lewis relationships (Eqs. (3) and (4)) are more representative of irrigation conditions, particularly those of long duration. Fourth as noted above, the irrigation of freshly tilled soil is one of the most important design conditions as well as one of the most difficult management conditions and was not represented in the original formulations. And finally, the evolution of intake families from ring data suffers from the fundamental differences in infiltration under a static and moving water surface.

Surface irrigation has now advanced 30 years. A new generation of field evaluation methods, a larger data base, and more useful simulation models have been developed. In 2004 it was decided to revise the basis and scope of the USDA–NRCS intake families. The revisions were based on five principles or assumptions:

1. The availability of data in the form of Eqs. (3) and (4) is much greater for furrow systems than for either borders or basins. Consequently, the reference family structure is formulated for furrow irrigation and then modified for borders and basins. This is a reversal from the original development.
2. The intake families should encompass both initial irrigation of newly tilled soil and irrigations of previously irrigated furrows since the intake characteristics are usually reduced after the first irrigation. It was decided that the basic reference family of curves would be for the initial irrigation or freshly tilled condition. Changes due to previous irrigations have been estimated from field experience and expressed as a modification of the reference family.
3. The intake families would still be denoted with numbers varying from 0.02 to 4.00 and have units of inches per hour. However, rather than base these family values of the nebulous concepts of Eqs. (8) and (9), they would be based on the average infiltration rate during the first 6 h of irrigation, or ''6 h intake rate.'' In other words, the 6 h intake rate is determined by the cumulative intake that occurs in the first 6 h of irrigation divided by the 6 h or 360 min interval. For initial continuous flow irrigations the 6 h intake rate is essentially the same as the original family designation as shown in Fig. 1, but the 6 h intake rates for subsequent irrigations are less. Table 2 shows the 6 h intake rates in mm/h for each soil and irrigation regime.

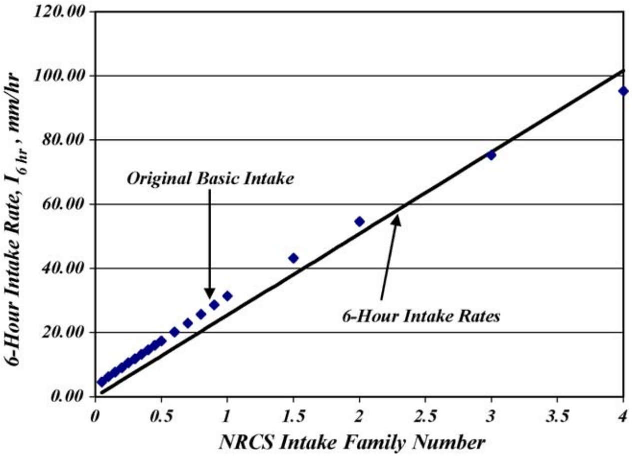

Fig. 1 – Comparison between the 6 h intake rate and the basic intake rate of the original SCS intake families.

4. The effect of surge flow for initial irrigations is assumed to be approximately the same as the effect of prior irrigations under continuous flow. Intake under surge flow systems during subsequent irrigations is based on adjustment of the initial irrigation surge flow intake.
5. The exponent a for borders and basins is the same as for furrows. This is the same assumption made in the original development.

4. Developing the basic furrow intake family

4.1. *Reference furrow irrigation data*

The USDA–NRCS revised intake families now involve four sets of functions for furrow irrigation and four intended for use with border and basin irrigation. These four are: (1) a family for freshly formed furrows representing the initial irrigation of the season; (2) a family for furrows that have been previously irrigated; (3) a family for surged applications in freshly tilled furrows; and (4) a family for surged applications in previously surge irrigated furrows. The four sets of families for border and basin irrigation are the same except modified for differences in wetted perimeter.

Several sources of continuous flow furrow evaluation data were utilized to formulate the various furrow intake families. Fangmeier and Ramsey (1978) reported a series of seven detailed evaluations in precision furrows in a fine sandy loam soil in Arizona. Elliott et al. (1980) reported on more than 100 field evaluations of furrow infiltration and advance functions at five sites in Colorado having soils ranging from loamy sand to clay loam. Walker and Humpherys (1983) reported on four continuous and surge flow comparisons from a sandy loam site in Utah and a silty loam site in Idaho. Scaloppi et al. (1995) evaluated two tests from two sites in California and Brazil but did not describe the soils involved. And finally, the Irrigation Training and

Table 2 – The 6 h intake rates for the furrow-based reference intake families

NRCS intake family	Soil texture	Initial continuous flow irrigation, 6 h intake rate (mm/h)	Later continuous flow irrigation, 6 h intake rate (mm/h)	Initial surge flow irrigation, 6 h intake rate (mm/h)	Later surge flow irrigation, 6 h intake rate (mm/h)
0.02	Clay	0.55	0.43	0.46	0.40
0.05	Clay	1.40	1.07	1.14	0.99
0.10	Clay	2.52	1.88	2.02	1.74
0.15	Clay	3.68	2.69	2.91	2.47
0.20	Clay loam	4.90	3.51	3.80	3.21
0.25	Clay loam	6.14	4.32	4.70	3.93
0.30	Clay loam	7.42	5.13	5.60	4.65
0.35	Silty	8.72	5.93	6.50	5.37
0.40	Silty	10.04	6.73	7.39	6.07
0.45	Silty loam	11.36	7.51	8.28	6.76
0.50	Silty loam	12.70	8.29	9.16	7.44
0.60	Silty loam	15.37	9.82	10.89	8.77
0.70	Silty loam	18.04	11.30	12.58	10.06
0.80	Sandy loam	20.69	12.74	14.23	11.30
0.90	Sandy loam	23.32	14.13	15.84	12.50
1.00	Sandy loam	25.93	15.49	17.41	13.66
1.50	Sandy	38.53	21.73	24.72	18.93
2.00	Sandy	50.65	27.27	31.34	23.53
4.00	Sandy	100.73	46.57	55.37	38.79

Research Center at the California Polytechnic State University in San Luis Obispo, California list 20 measurements on their website: http://www.itrc.org/index.html.

Surge flow tests from Utah, Colorado, Texas, Oklahoma, Arkansas, Montana, Washington, and Kansas were reported by Stingham et al. (1988). These data encompass about the same range of conditions as those for the continuous flow tests but involve many more sites. The number of individual tests was about one half of those reported for continuous flow.

Taken together, these data represent continuous and surge flow conditions, soil types ranging from clay and clay loam to sandy loams and loamy sands, flows that range from 0.25 lps to 4 lps, and slopes ranging from nearly zero to 0.01 m/m. These sources of furrow data were not intended to be exhaustive but representative. Nevertheless, the authors believe that few furrow irrigation conditions lie substantially outside these ranges.

4.2. *Furrow intake families*

In order to develop furrow irrigation intake families, the available data were divided into initial and latter continuous flow and initial and latter surge flow tests. As one might suspect, the variations are large. Since the intake families are intended as starting points when actual data are unavailable, it was decided to formulate the families as functions of the initial continuous flow irrigations in order to provide the user with some degree of flexibility in their application.

The values of the a, K, and F_0 parameters for initial continuous flow furrow irrigation were selected and correlated with the NRCS Family Number, Fn. Then, general functions were developed to adjust the parameters to later continuous flow irrigation and both surge flow conditions. This analysis was perhaps more qualitative and subjective than quantitative as the data are widely scattered due to variations in field length, furrow shape, and slope.

Figs. 2–4 show the resultant furrow intake family parameters for Eq. (3) when irrigating freshly tilled furrows with a continuous inflow. Equations for each intake parameter are given below.

$$a_{\mathrm{ref}} = \frac{(0.1571 + 2.5739 \times \mathrm{Fn})}{(1 + 3.6940 \times \mathrm{Fn} - 0.1149 \times \mathrm{Fn}^2)} \qquad (16)$$

$$F_{0\,\mathrm{ref}} = 0.000454(1.0149 - e^{-0.5596 \times \mathrm{Fn}}) \qquad (17)$$

$$K_{\mathrm{ref}} = 0.00247(\mathrm{Fn} + 0.00319)^{0.5817} \qquad (18)$$

4.3. *Adjusting for irrigation conditions*

The reference intake functions are based on freshly tilled or initial irrigation of furrows but can be used to generate intake parameters for later continuous flow, and the surge flow conditions by multiplying these functions by an ‘‘irrigation condition factor, ICF’’. For instance, a typical later continuous intake can be estimated by ICF of 0.80. A typical value for the initial surge flow factor, which integrates the initial continuous flow and surge flow conditions, is 0.85. And, a latter surge flow factor should be about 0.75. These factors can be

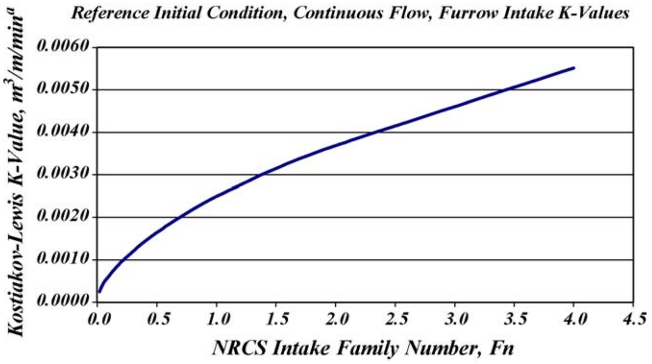

Fig. 2 – Continuous flow values of the Kostiakov–Lewis ‘‘a’’ for initial irrigations.

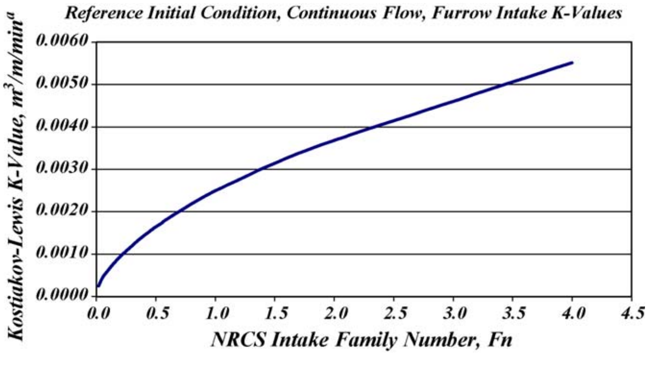

Fig. 3 – Values of the Kostiakov–Lewis "*K*" for the reference condition.

adjusted by the user to better simulate local conditions when local data become available.

Other changes in furrow conditions such as wheel traffic compaction can also be accounted for using the ICF parameter. Although some data are available such as the report by Walker and Humpherys (1983), it is insufficient for more than qualitative comparison. In the Walker and Humpherys (1983) data, the effects of surge flow and wheel compaction are nearly the same in both the sandy loam soil tests in Utah and the silty clay loam tests in Idaho.

4.4. *Reference flow and wetted perimeter*

Two furrows with identical soil characteristics will exhibit different infiltration characteristics if the hydraulic conditions at the surface are different. These effects are generally accounted for by estimating the variations in wetted perimeter which can be caused by differences in roughness, constructed cross-section, furrow slope, and the flow rate in the furrow. The effects associated with variations in wetted perimeter have to be included in the definition and values of K and F_0 in Eq. (3). Thus, these empirical parameters must represent not only specific soils characteristics but also be functions of the surface discharges and wetted perimeters.

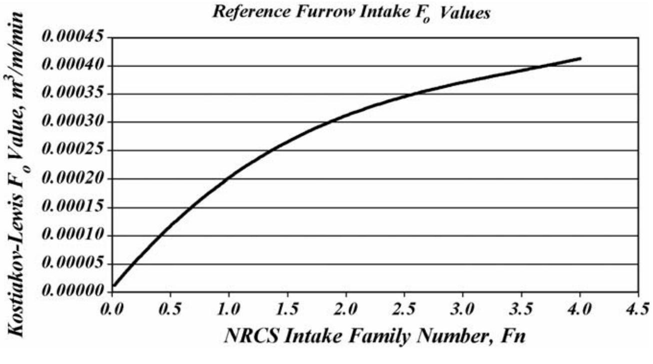

Fig. 4 – Values of the Kostiakov–Lewis "F_0" for the reference condition.

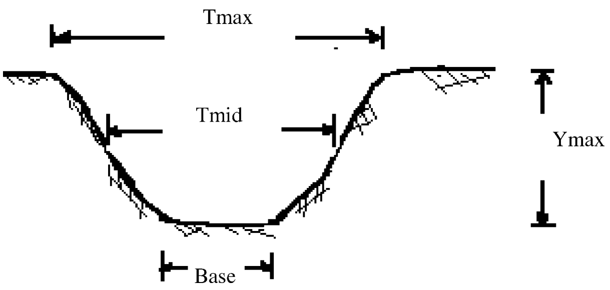

Fig. 5 – A typical furrow cross-section.

The furrow discharge associated with the respective data sets noted in Section 4.1 and used to determine the furrow intake equations was fitted by least squares to an expression representing the full range of the NRCS intake families. This "reference" discharge has been expressed as:

$$Q_{\mathrm{ref}} = 0.432 + 1.79 \times \mathrm{Fn} - 0.225 \times \mathrm{Fn}^2 \tag{19}$$

in which Q_{ref} is the reference discharge, in lps, for a specific intake family number, Fn. The values of Q_{ref} are assumed to the same for all furrow irrigation intake families, i.e., initial and later continuous flow as well as initial and later surge flow conditions.

Associated with Q_{ref} is a reference wetted perimeter, $\mathrm{WP}_{\mathrm{ref}}$, expressed in m, necessary to adjust intake parameters for variations in cross-section, roughness, and slope. Again using the available field data to determine a relationship between intake family and $\mathrm{WP}_{\mathrm{ref}}$ yielded:

$$\mathrm{WP}_{\mathrm{ref}} = 0.298 \times (\mathrm{Fn} - 0.1417)^{0.548} \tag{20}$$

Since the horizontal intake in furrows is different than the vertical intake from the bottom of the furrows and should be different than the one-dimensional intake in borders and basins, it is necessity to define an "equivalent" wetted perimeter, W_{eqv} that could be used to convert furrow reference intake parameters to border and basin values. The nature of this relationship is not currently known and thus is assumed to be the same as used in the origin work (USDA, 1984) expressed as follows:

$$\mathrm{WP}_{\mathrm{eqv}} = \mathrm{WP}_{\mathrm{ref}}^{0.4} \tag{21}$$

where W_{eqv} is expressed in m.

5. Adjusting infiltration for changes in irrigation characteristics

5.1. *Adjusting infiltration for changes in furrow wetted perimeter*

Defining a reference discharge leads to the definition of reference depths, cross-sectional areas, and wetted perimeters if values of the Manning *n* coefficient, field slope, and cross-sectional shape are known. Consider the typical furrow cross-section shown in Fig. 5.

Elliott et al. (1980) report on a field evaluation of more than 100 furrow evaluations at five sites in Colorado during 1979 and 1980 which involved furrow profile measurements along the furrow before and after irrigation. In evaluating these data, Elliott and Walker (1982) found that the wetted perimeter and cross-sectional area could be expressed as simple power functions of depth, i.e.:

$$WP = \gamma_1 y^{\gamma_2} \tag{22}$$

where WP is the wetted perimeter of the furrow in m, y is the flow depth in m, and γ_1 and γ_2 are numerical fitting parameters; and

$$A = \sigma_1 y^{\sigma_2} \tag{23}$$

in which A is the cross-sectional area of the furrow in m^2,and σ_1 and σ_2 are numerical fitting parameters. The hydraulic section can be computed by combining Eqs. (22) and (23):

$$A^2 R^{4/3} = \rho_1 A^{\rho_2} \tag{24}$$

in which,

$$\rho_2 = \frac{10}{3} - \frac{4\gamma_2}{3\sigma_2} \tag{25}$$

and,

$$\rho_1 = \frac{\sigma_1^{10/3-\rho_2}}{\gamma_1^{4/3}} \tag{26}$$

Measuring a furrow cross-section in the field and then calculating the values of the empirical parameters in the preceding equations can be a tedious exercise. One simple approach is to use the four measurements shown in Fig. 5 and then assuming a compound trapezoidal shape such that the values of γ_1, γ_2, σ_1, and σ_2 can be computed by the equations presented in Appendix A:

Utilizing these geometric relationships, the cross-sectional flow area can be estimated as a function of the reference flow, Q_{ref} expressed in m^3/s, using the field slope, S_0 and the Manning formula for the values of resistance, n:

$$A_{\mathrm{ref}} = \left[\frac{Q_{\mathrm{ref}}^2 n}{\rho_1 S_o}\right]^{1/\rho_2} \tag{27}$$

Then the reference flow depth, y_{ref}, is computed from Eq. (23) using the reference cross-sectional area found in Eq. (27). And finally, the reference wetted perimeter, WP_{ref}, is found from Eq. (22).

Using this same methodology, the wetted perimeter created by another flow, slope, or roughness, WP_a, can be computed. Then the infiltration parameters can be adjusted as follows for the initial or later continuous and surge flow:

$$a = ICF \times a_{\mathrm{ref}} \tag{28}$$

$$K = ICF \times K_{\mathrm{ref}} \times \left[\frac{WP_a}{WP_{\mathrm{ref}}}\right] \tag{29}$$

and

$$F_0 = ICF \times F_{0\ \mathrm{ref}} \times \left[\frac{WP_a}{WP_{\mathrm{ref}}}\right] \tag{30}$$

where ICF is defined in Section 4.3.

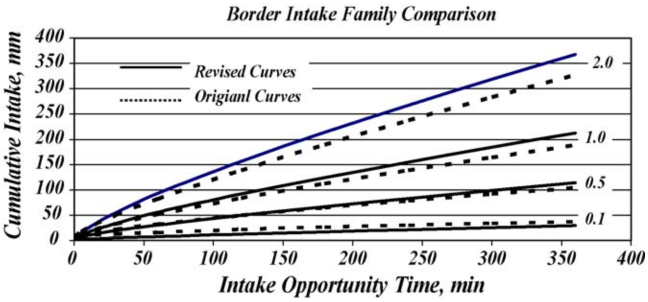

Fig. 6 – One-dimensional, initial condition, cumulative intake for selected original and revised NRCS–USDA intake families.

5.2. *Border and basin intake families*

To determine the Kostiakov–Lewis reference parameters for border and basin irrigation, it has been usual practice to assume that the infiltration through the furrow perimeter is uniform. This same assumption is made here except the uniformity is assumed over the equivalent wetted perimeter, W_{eqv} defined by Eq. (21). It is also assumed that the exponent is the same for both furrow and border/basin situations, although adjusted for initial or later conditions.

To convert from furrows to borders or basins, therefore, values of furrow K and F_0 coefficients are divided by W_{eqv} and adjusted for irrigation condition to estimate the values of k and f_0 for Eq. (4):

$$k = \frac{ICF \times K_{\mathrm{ref}}}{WP_{\mathrm{eqv}}} \tag{31}$$

$$f_0 = \frac{ICF \times F_{0\ \mathrm{ref}}}{WP_{\mathrm{eqv}}} \tag{32}$$

6. Comparing old and new

In today's irrigation engineering environments the primary use of the intake family concept is in simulating and designing surface irrigation systems. A comparison of the cumulative intake of revised and original intake curves for one-dimen-

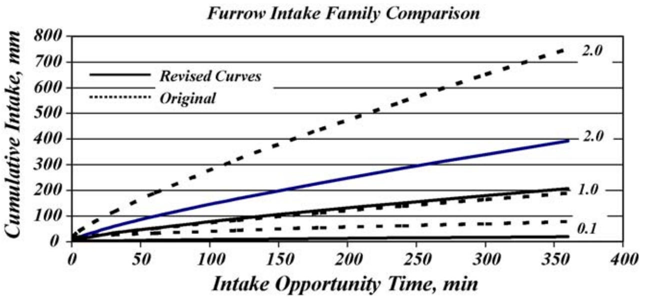

Fig. 7 – Initial condition furrow cumulative intake for selected original and revised NRCS intake families.

sional infiltration is shown in Fig. 6. Fig. 7 and illustrates the differences between the original and revised intake families for furrow irrigation.

7. Conclusions

The historic USDA–NRCS intake families have been revised to be more consistent with current practices and software. This paper has described the procedures and assumptions used during the revision and presented the revised intake families in their mathematical form. A comparison of the original and new curves is shown. The new curves estimate higher infiltration for the curves numbered about 1.0 and higher. This means that advance will be slower. The new estimates are lower for the curves numbered below 0.5 so advance will be faster. Between these ranges, the original and new curves will estimate about the same infiltration, advance and recession. Thus, while the original and new intake curves produce approximately the same simulation results for border irrigation, the basis for the curves is substantially different. And though not demonstrated here, the differences between simulated advance and recession results for furrow irrigation are substantially different. The families for both furrow and border/basin irrigation have been extended from initial irrigations to latter ones as well as initial and latter surge flow conditions.

The strongest facet of the new curves is the furrow intake families since they are developed from a relatively good field data base. The weakest is the family structure for borders and basins because these families are based on a conversion between the two and one-dimensional intake which relies on a simplistic assumption that will need to be tested over time. In either case, the new intake families should be viewed as starting points for analyses until adequate field data can be collected.

Appendix A

$$\gamma_2 = \frac{\log\left[\left[\mathrm{Base} + \sqrt{\mathrm{Y}_{\mathrm{max}}^2 + (T_{\mathrm{mid}} - \mathrm{Base})^2} + \sqrt{\mathrm{Y}_{\mathrm{max}}^2 + (T_{\mathrm{max}} - T_{\mathrm{mid}})^2}\right] / \left[Base + \sqrt{\mathrm{Y}_{\mathrm{max}}^2 + (T_{\mathrm{mid}} - \mathrm{Base})^2}\right]\right]}{\log 2} \tag{A1}$$

$$\gamma_1 = \frac{\left[\mathrm{Base} + \sqrt{\mathrm{Y}_{\mathrm{max}}^2 + (T_{\mathrm{mid}} - \mathrm{Base})^2} + \sqrt{\mathrm{Y}_{\mathrm{max}}^2 + (T_{\mathrm{max}} - T_{\mathrm{mid}})^2}\right]}{\mathrm{Y}_{\mathrm{max}}^{\gamma_2}} \tag{A2}$$

$$\sigma_2 = \frac{\log[((\mathrm{Y}_{\mathrm{max}}/2)((\mathrm{Base}/2) + T_{\mathrm{mid}} + (T_{\mathrm{max}}/2)))/(\mathrm{Y}_{\mathrm{max}}/2)((\mathrm{Base}/2) + (T_{\mathrm{mid}}/2))]}{\log 2} \tag{A3}$$

$$\sigma_1 = \frac{(\mathrm{Y}_{\mathrm{max}}/2)((\mathrm{Base}/2) + T_{\mathrm{mid}} + (T_{\mathrm{max}}/2))}{\mathrm{Y}_{\mathrm{max}}^{\sigma_2}} \tag{A4}$$

REFERENCES

Elliott, R.L., Walker, W.R., 1982. Field evaluation of furrow infiltration and advance functions. Trans. ASAE 25 (2), 396–400.

Elliott, R.L., Neff, M.E., Binder, C.W., Ley, T.W., Salazar, L.J., Walker, W.R., Hart, W.E., Skogerboe, G.V., Karmeli, D., 1980. Furrow irrigation field evaluation data – 1977–1979. Internal Report, Department of Agricultural and Chemical Engineering, Colorado State University, Fort Collins, Colo., (unpublished).

Fangmeier, D.D., Ramsey, M.K., 1978. Intake characteristics of irrigation furrows. Trans. ASAE 21 (4), 696–705.

Irrigation Training and Research Center, California Polytechnic State University, San Luis Obispo. http://www.itrc.org/index.html. Data from 1997 to 2002.

Philip, J.R., 1957. The theory of infiltration: 4. Sorptivity and the initial moisture content; and 5. The influence of the initial moisture content. Soil Sci. 84, 257–337.

Scaloppi, E.J., Merkley, G.P., Willardson, L.S., 1995. Intake parameters from advance and wetting phases of surface irrigation. J. Irrig. Drain. Div., ASCE 121 (1), 57–70.

Stingham, G.E., Duke, H.R., Walker, W.R., Humphreys, A.S., Evans, R.G., Bassett, D.L., Miller, D.E., Aarstad, J.S., Blair, A.W., Smerdon, E.T., McCornick, P.S., Podmore, T.H., 1988. Surge flow irrigation. Final report of the Western Regional Project W-163. Utah Agricultural Experiment Station. Utah State University, Logan, Utah, 92p.

US Department of Agriculture, Natural Resources and Conservation Service, 1974. National Engineering Handbook. Section 15. Border Irrigation. National Technical Information Service, Washington, DC, Chapter 4.

US Department of Agriculture, Natural Resources and Conservation Service, 1984. National Engineering Handbook. Section 15. Furrow Irrigation. National Technical Information Service, Washington, DC, Chapter 5.

US Department of Agriculture Natural Resources and Conservation Service, 2005. National Engineering Handbook, Part 623, Surface Irrigation. National Technical Information Service, Washington, DC, Chapter 4.

Walker, W.R., Humpherys, A.S., 1983. Kinematic-wave furrow irrigation model. J. Irrig. Drain. Div., ASCE 109 (4), 377–392.