A mathematical model for surge flow border irrigation
by Toraj Ghofrani

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Agricultural Engineering
Montana State University
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Abstract:
The purpose of this study was to review the theory of available models and select an appropriate model
for surge flow border irrigation. Field data taken from surge flow border irrigation was used to evaluate
the performance of the selected model. A FORTRAN model named BRDRFLW was selected for
evaluation because it was commercially available, affordable and it could simulate the complete
process of irrigation. BRDRFLW was designed for conventional continuous flow border irrigation. The
model had three options to generate the solution parameters, the zero-inertia option, the
kinematic-wave option, and the hybrid of the two. The data from Merriam et al. (1978) was used to
calibrate the model. The zero-inertia option of the BRDRFLW model produced the best results. The
zero-inertia option was then tested for surge flow border irrigation. The result of this study indicated
that the BRDRFLW model can be used to predict the process of surge flow border irrigation. However,
this study has been done based on limited field data. More field data are required in addition to some
modifications of the model's software before the BRDRFLW model can be reliably used to predict the
performance of the surge flow border irrigation.

A MATHEMATICAL MODEL FOR

SURGE FLOW BORDER IRRIGATION

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College of Graduate Studies.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES--continued

ABSTRACT

The purpose of this study was to review the theory of available models and select an appropriate model for surge flow border irrigation. Field data taken from surge flow border irrigation was used to evaluate the performance of the selected model. A FORTRAN model named BRDRFLW was selected for evaluation because it was commercially available, affordable and it could simulate the complete process of irrigation. BRDRFLW was designed for conventional continuous flow border irrigation. The model had three options to generate the solution parameters, the zero-inertia option, the kinematic-wave option, and the hybrid of the two. The data from Merriam et al. (1978) was used to calibrate the model. The zero-inertia option of the BRDRFLW model produced the best results. The zero-inertia option was then tested for surge flow border irrigation. The result of this study indicated that the BRDRFLW model can be used to predict the process of surge flow border irrigation. However, this study has been done based on limited field data. More field data are required in addition to some modifications of the model's software before the BRDRFLW model can be reliably used to predict the performance of the surge flow border irrigation.

CHAPTER 1

INTRODUCTION

Irrigation, an age-old art, is the artificial application of water to soil for crop production to meet the food and fibre needs. Irrigation is essential when the amount and timing of rainfall is inadequate to satisfy the crops' moisture demand. The exponential growth of the world's population has had three major impacts on irrigation. One impact is the increase in food and fibre demand for a rapidly growing population. The second impact is that the agricultural land area is shrinking every year by approximately half a million hectares to make way for industrial expansion, highways, parks, residential areas, and other nonfood producing uses (Pair et al., 1983). The third impact is that the groundwater aquifers, one of the major sources of irrigation water, are being depleted due to increasing water demands. Because of this rapid population growth, better management and use of irrigation water is vital for the future.

Surface, sub-surface, sprinkler, and drip are the four common methods of irrigation. In the surface methods water flows by gravity from a channel at the upper end of the

field. In sub-surface irrigation, water is injected below the soil surface to create an artificial water table in the root zone area. With sprinkler irrigation, water is sprayed into the air to fall on the soil. In drip irrigation, water is delivered to the soil surface near the base of the plants using small diameter plastic pipes and emitters. Each method of irrigation has its own advantages and disadvantages which must be judged according to a particular situation.

Surface irrigation is the most popular irrigation method practiced in the world, probably because of the smaller initial investment required as compared to other types of irrigation systems. Of the total land area cultivated in the world, only 20% is irrigated. Out of this irrigated land, 95% is irrigated using the traditional surface irrigation methods (Melvyn, 1986).

Surface irrigation is often regarded as being inefficient and sometimes wasteful. High runoff and deep percolation losses are two contributives to inefficiency. Sub-surface, sprinkler, and drip irrigation have been used increasingly in the last two decades mainly because of their ability to reduce runoff and deep percolation losses as well as their ability to reduce the intensive labor required to irrigate. The energy crises of the 1970's caused a re-evaluation of the economics of irrigation method that involves large energy inputs to the system. Rifkin (1980)

points out that United States agriculture, the most mechanized in the world, uses 10 calories of energy for each calorie which it produces; therefore, the energy cost for irrigation is surpassing the energy produced by irrigation. Because of its low energy consumption, surface irrigation will remain popular for the foreseeable future. It is not surprising that irrigation designers in recent decades have expended tremendous effort to improve surface irrigation.

Check basins, furrows, and borders are the three main surface irrigation methods. Check basins are the most common and simplest method of surface irrigation. The field is divided into small areas with nearly level surfaces. In each area basins are formed by constructing ridges around the small areas so that water can be retained and allowed to infiltrate gradually into the soil. The furrow method of surface irrigation utilizes small channels between the crop rows through which water can flow, and from which water can infiltrate, and move laterally to irrigate the area between furrows. The border method of irrigation uses parallel ridges to guide a sheet of water down slope to the lower end of the field. The water supply should normally be shut off before the advance front of the flowing sheet of water reaches the lower end of the border to minimize runoff and deep percolation losses. To adequately irrigate the lower end of the border, some runoff or ponding of water may be

required. The border strip should have little or no transverse slope. Border irrigation can be the most efficient irrigation method and require the least amount of labor if the border system is properly designed.

In a well managed and designed systems, the water is advanced to the lower end of the border as quickly as possible in an effort to minimize the differences in intake opportunity time along the border strips. In traditional border irrigation, a continuous delivery of water using a large stream size is used to advance the water to the end of the border. The continuous delivery system is often inefficient due to excessive runoff which causes drainage problems at the lower end of the borders.

Stringham et al. (1979) introduced surge flow irrigation as a new operational practice which can improve traditional surface irrigation by minimizing runoff and deep percolation losses. The surge flow technique utilizes on-off cycles to create a series of short pulses of water during "on" periods and shut off water during "off" periods (Bishop et al., 1981). The soil is believed to seal during the "off" periods, thereby transporting the next surge quickly towards the lower end of the field and reducing deep percolation losses at the upper end of the field. At the same time, through using on-off cycles, runoff can be better controlled by simply applying less water. Stringham (1979) indicates that surge flow should be economically feasible on

nearly 9 million hectares of irrigated land in the United States. This is approximately one third of all irrigated land in the United States.

Most early surge flow research has been devoted to furrow irrigation. The first testing of surge flow on borders was done in Montana in 1983 (Westesen et al., 1985).

In the last decade a number of mathematical models have been developed to describe the border irrigation process. All of the contemporary models are for traditional continuous flow border irrigation. The objective of this study is to evaluate the adaptability of existing models for surge flow border irrigation. The following steps are necessary to accomplish this objective:

1- Study the theory of available models.

2- Select an appropriate model.

3- Calibrate the selected model.

4- Test the selected model for surge flow border irrigation.

5- Suggest possible modifications necessary to adapt the selected model to surge flow border irrigation.

CHAPTER 2

BACKGROUND INFORMATION

Border Irrigation Theory

Parallel ridges are used in the border method of irrigation to guide a sheet of flowing water down the slope using gravitational force. Borders are long parallel strips separated by low ridges with a uniform smooth slope in the direction of the water flow. Borders have little or no transverse slope. In operation, a stream of water spreads and flows down the strip and is guided by the border ridges. The stream size must be large enough to spread evenly over the entire border width without over-topping the border ridges. To avoid runoff, water is shut off before the advancing front of the sheet of water reaches the lower end of the border. The lower end of the border is then irrigated by water temporarily stored on the upper end of the border. Michael (1978) described the advantages of the border method of irrigation as follows: (1) border ridges can be constructed economically with simple farm implements, (2) labor requirements can be greatly reduced, (3) uniform distribution and high water application efficiencies can be achieved if the system is properly designed, (4) a larger

stream size can be used, and (5) adequate surface drainage can be provided if outlets are available.

Border Irrigation Hydraulics

An understanding of border irrigation hydraulics, is necessary to evaluate the mechanism of border operation. All variables in border irrigation hydraulics can be divided into two categories, exogenous, and endogenous. Exogenous variables are independent constants whose values are known prior to analysis. Endogenous variables are dependent variables whose values are not known, but are determined as part of the solution information. The exogenous and endogenous variables for border irrigation hydraulics are summarized in Table 1.

Table 1. Border irrigation variables.

Variables	Endogenous	Exogenous
Velocity of Advance	*	
Velocity of Recession	*	
Time of Advance	*	
Time of Recession	*	
Velocity of Surface Flow	*	
Depth of Surface Flow	*	
Depth of Infiltration	*	
Volume of Surface Runoff	*	
Volume of Deep Percolation	*	
Recession Lag Time	*	
Total Irrigation Time	*	
Inflow Rate		*
Slope		*
Surface Roughness		*
Infiltration Charactristics		*

The exogenous variables must be considered carefully in order to obtain a correct solution for the border irrigation problem. Inflow rate, land slope, surface roughness, and a discussion of infiltration follows.

Inflow Rate

In border irrigation the inflow rate is normally expressed as a constant flow rate per unit width of border ($L^3/T \times L$ where L is the units of length and T is the units of time). This represents a flow of water which is the same for all unit widths of the border.

The classification of the state of flow is very complicated once the inflow at the upper end of the border begins. The state of flow at the upper end of the border is neither the same as shallow, low velocity flow that occurs during recession, nor the same as deep, low velocity flow that occurs when water is ponded on the surface (Jensen, 1983). This aberration in the state of flow is due to the gradually varied and usteady infiltration rate of the soil. The constant flow considered in most studies is assumed to represent a typical flow during irrigation.

The flow can be reliably described as unsteady varied flow at a sub-critical state since the Froud numbers are less than unity. The state of flow can be changed to transitional or turbulent at the upper end of the border even if the Reynolds number remains below 1000. Inflow is an important variable since the results can be greatly

affected by inflow changes.

Land Slope

Land Slope is fixed during a particular irrigation. The slope can be changed to provide better irrigation management, but this requires land grading. A downward slope is considered to be positive and is expressed in a dimensionless form of L/L.

Surface Roughness

Surface roughness is a variable which changes from one border to another as well as one soil to another. Surface roughness, therefore, is very difficult to estimate. Many empirical equations have been developed in an effort to estimate the value of surface roughness for various soils under different conditions. Manning "n" is widely used as a roughness parameter and is defined by the Soil Conservation Service (SCS) as well as other sources describing open channels. Jensen (1983) mentioned in his study that the results are less sensitive to surface roughness than the other exogenous variables.

Infiltration

Infiltration is the movement of surface water into the soil. The infiltration characteristics are perhaps the most important variables when deciding which method of irrigation to use. The velocity at which water can percolate through the soil is called the infiltration rate. Melvyn (1986) indicates that soils with low to medium infiltration rates

(0-30 mm/h) are suitable for surface irrigation. Soils with high infiltration rates (greater than 30 mm/h) are suitable for sprinkler or trickle irrigation.

Infiltration is affected by soil properties as well as moisture content. The infiltration rate is much higher at the beginning of an irrigation than it is several hours later. This higher rate occurs because the moisture tension is lower near the wetted surface and higher below the surface of the soil. The moisture gradient causes a downward pulling of the water into unsaturated soil. Once the soil is saturated, the moisture gradient is minimized and gravity becomes the dominant force causing infiltration to continue (Hansen et al., 1980). The precise measurement of the infiltration rate is not yet possible because of the microscopic, hetereogeneous, and anisotropic structure of the soil particles. As early as 1911, researches attempted to express an empirical equation describing the accumulated infiltration and elapsed time for design purposes. The most widely used infiltration rate equation today is defined by the USDA, Soil Conservation Service (1974), by classifying all soils into intake families. The general equation has the form of:

$$z = Kt^A + C \qquad (2.1)$$

z, and t = accumulated intake, and intake opportunity time.
K, A, and C = constants representing soil intake family.

All endogenous variables can be summarized schematically in Figure 1 (Jensen,1983).

Figure 1. Schematic description of border irrigation phases.

Advance Phase

The advance phase is the total irrigation time during which water advances in the border from the upper to the lower end. Unit flow, slope, surface roughness, and infiltration are four major factors affecting the advance phase. These effects are summarized in the table 2.

Table 2. Advance phase effects.

Cause	Type of perturbation	Effect on advance Time (min.)
Inflow Rate	increased	would be decreased
	decreased	would be increased
Slope	steepened	would be decreased
	flattened	would be increased
Surface Roughness	increased	would be increased
	decreased	would be decreased
Infiltration Rate	increased	would be increased
	decreased	would be decreased

Jensen (1983) defines the remaining phases as follows.

Storage Phase

The storage phase is "the total irrigation time between the end of advance and inflow shut-off." If shut-off occurs first, this phase would be equal to zero.

Depletion Phase

The depletion phase is "the total irrigation time between inflow shut-off and the beginning of recession at the upper end of the border". This phase is also referred to as lag time.

Recession Phase

The recession Phase is "the total irrigation time between the beginning of the recession at the upper end of the border and the disappearance of the last water from the field surface."

The irrigation water infiltrated into the soil is related to the intake opportunity time (the time between the advance and recession curves in Figure 1). The more constant the intake opportunity time over the border length, the better the irrigation.

The Surge Flow Concept

The word surge was referred to by Chow (1959) to describe a rapid varied unsteady flow (moving hydraulic jump) due to abrupt decrease or increase in flow. Surge was later used in conjunction with flow to describe a new operational practice in irrigation called surge flow

irrigation. On-off cycles were used to create a series of surges during the "on" periods and cutback water during "off" periods. The soil surface appears to become partially sealed during "off" periods. Surface sealing is undoubtedly the most important feature of surge flow irrigation. The next section will pursue the concept of surface sealing from an historical perspective.

Surface Sealing

Ellison et al. (1945) referred to Wollny who in 1877 as perhaps the first researcher to recognize the reduction in soil permeability caused by rainfall. Duley et al. (1939) photographed the changes in the soil surface and concluded that the breaking down of aggregates (Figure 2 and 3) was a key factor in reducing infiltration.

ONE CENTIMETER

Figure 2. Soil surface before rainfall (Duley et al., 1939)

ONE CENTIMETER

Figure 3. Soil surface after rainfall (Duley et al., 1939)

Ellison (1945), in a different study, explained the mechanism behind surface sealing caused by rainfall. He stated that the first raindrops striking the soil surface break down aggregates and release the fine particles of silt and clay. The splashing water carries some of the silt and clay particles as they land on the soil surface. As this mixture of water, silt, and clay particles percolates through the soil, the silt and clay particles are filtrated out immediately below the soil surface. These deposited particles of silt and clay were believed to contribute to the surface sealing. He also named puddling and compaction of the soil under rainfall as additional factors tending to reduce the infiltration capacity of the soil.

McIntyre (1958) measured the permeability of the soil crusts affected by surface sealing under rainfall impact. He

distinguished two different layers in the soil crust: first, a thin compacted sealed skin of about 0.1 mm followed by a second layer a few centimeters thick that he called the "washed-in" layer. The permeability of these two layers was measured to be, respectively, 5×10^{-7} cm/sec and 5×10^{-6} cm/sec as compared to a permeability of 10^{-3} cm/sec for underlying soil which is not effected by surface sealing. These measurements showed that the compacted sealed skin had a permeability 2000 times less than underlying soil. The "washed-in" layer, however, had a permeability 200 times less than the underlying soil. Both of them cause a remarkable reduction in the soil's permeability.

Tacket et al. (1965) recognized that, under raindrop impact, different soils have different susceptibilities to crust formation. They made an attempt to define the soil properties which govern the crust characteristics by testing soils of different structure and composition. It was finally concluded that clay particles are the dominant factor obstructing the penetration of water and reducing permeability.

Edwards et al. (1969) used a numerical solution for a water-flow equation to estimate infiltration into a homogeneous soil which was sealed by raindrop impact. A fifty percent reduction in infiltration by surface sealing was reported in a 2-hour period. Walker et al. (1982) summarized a decade of research on the surge flow concept.

The theory of surface sealing under rainfall impact was confirmed for irrigation, except that in irrigation the impact forces were absent.

Coolidge et al. (1982) confirmed the theory of surface sealing that "as water infiltrates after the first pulse, the lubricated particles in the surface soil may be reoriented horizontally and in a plate fashion that would greatly reduce infiltration in the wetted section of furrow." This concept is presented schematically in the figure below.

Figure 4. Clay and silt particles before (left) and after (right) surface sealing.

Although there is still some ambiguity regarding the surface sealing mechanism, the fact that the soil's permeability will be decreased during "off" periods of surge flow irrigation is now universally accepted.

Surge Flow Irrigation

Since the mid 70's researchers have accepted the concept of surface sealing as being a positive factor for irrigation purposes. Karmeli et al. (1974) utilized surge flow irrigation or "pulse irrigation", as it was then called, to obtain a low application rate. The researchers defined the term pulse irrigation as a series of irrigation cycles in which each cycle included two phases: (1) the operational phase, and (2) the resting phase. Later, these phases were called the on-off cycle. The determination of the number of cycles and the time of each cycle was also introduced as a main factor in pulse irrigation design.

Zur (1976) applied pulse irrigation principles for trickle irrigation to obtain low application rates. A time-averaged hourly water application rate was used in laboratory tests to define the pulse water application regime. It was reported that "the volumetric soil water content distribution and the rate of advance of the wetting front in the soil columns behaved as if time-averaged water application rate was being applied continuously." He suggested that the pulsed water application method be used to control the wetting front of the soil during infiltration.

Levin et al. (1979) tested pulse (intermittent) irrigation and continuously applied trickle irrigation for horizontal and vertical distribution of water beneath the

soil. They reported a 26% loss below the root zone for continuously applied trickle irrigation but only 12% loss for the pulse method of irrigation. While pulse irrigation showed a clear advantage in reducing water loss below the root zone, the horizontal and vertical distribution was affected insignificantly.

Stringham et al. (1979) first employed the concept of surge flow for furrow irrigation. An automatic gated pipe with a microprocessor control unit was used to control the cut-back by changing the time cycle instead of the instantaneous flow rate. The researchers stated that when the valves were opened and closed half of the time the same average stream size would be achieved as if half of the flow ran all the time.

Lillevik (1980) studied the economical advantage of using automated surge flow irrigation. He found the use of microcomputer-controlled furrow irrigation would be promising on 75% of the labor intensive irrigated land in the United States. He argued that microcomputer-controlled furrow irrigation can benefit farmers by reducing labor requirements, improving the irrigation efficiency, and lowering the energy cost.

Bishop et al. (1982) conducted several tests to examine the advance and runoff from furrows under surge flow irrigation as compared to continuous flow irrigation. The advance time was reported to be longer for the continuous

flow treatment and it was concluded that surge flow irrigation accelerated the furrow advance per unit of water applied.

Podmore et al. (1982) tested the surge flow concept in furrow irrigated corn. The consumption of water was reported to be reduced by as much as 50% using the surge flow treatment. By reducing infiltration when using surge flow, more runoff was reported which led to lower efficiency for surge flow as compared to continuous flow. The yield was the same for the surge flow and continuous flow methods.

Podmore et al. (1983) tested different cycle times as well as cut-back after advance to obtain higher efficiency for surge flow furrow irrigation. For higher efficiency, they suggested that surge flow should be started with shorter cycle times at the beginning of irrigation and longer cycle times later.

Westesen et al. (1986) tested surge flow and conventional continuous flow for graded border irrigation. An application efficiency (average depth stored in root zone divided by average depth applied) of 83% was reported when using surge flow as compared to 48% for conventional continuous flow.

Advantages and Disadvantages of Surge Flow

Bishop et al. (1981) summarized the major advantages of the surge flow irrigation method over traditional surface irrigation as follows: (1) more efficient irrigation, (2)

more uniform water distribution, (3) more uniform advance across the field for the entire season, (4) longer runs without increasing inlet streams, (5) more uniform intake opportunity time, and (6) a capability for automation.

The major disadvantages of the surge flow method is its management which is much more complicated than traditional surface irrigation management. Surge flow requires the manager to determine inflow rate, time of application, cycle time and a cut-back strategy.

The amount of water needed to satisfy the soil moisture deficiency in the root zone is the controlling factor for cycle time. The more water required, the longer the cycle time. For the best flow sequence, the first cycle should be short while later cycles should be longer as water advances further down the field. By increasing the cycle time, the water advance over dry soil with each new cycle would be about the same. When water reaches the end of the field, the cycle time should be decreased to prevent runoff.

Cut-back strategy is also very important in surge flow management. Cut-back strategy is controlled by cycle time: the longer the cycle time, the longer the valves would be open causing more runoff at the end of the field. The cut-back system is a function of the soil type, infiltration rate, and variation in the speed of the surge and therefore very difficult to predict. Reddle (1981) used a radio-controlled water advance sensor, a radio receiver, and a

microcomputer to evaluate the infiltration rate and adjust the cycle time in an effort to control the cut-back system.

CHAPTER 3

MATHEMATICAL MODEL FOR BORDER IRRIGATION

The Concept of Mathematical Modeling

Mathematical modeling has been a controversial issue in modern science. Many field practitioners regard mathematical modeling as being useless because of its inability to reproduce the precise "reality". On the other hand, many scientists overestimate the ability of mathematical modeling and draw conclusions which the model was not intended to predict. Modeling is a very natural thing for human beings to do. Rivett (1972) called human beings model-building animals and traced the art of modeling in human history and confirmed the fact that models were commonly used thousands of years ago by Babylonians to predict the cycle of stars.

When experience in the real world is not possible or too expensive, models can be used to conveniently predict the future. A model is a way of simulating reality and can be used as a substitute for a system or an object. Models, however, should not be expected to be identical to that of a system or an object. Forrester (1968) stated that models cannot be proven to represent "reality" because "reality"

itself is subjected to imperfect information. Models, he said, are to be judged on a relative scale that approves or succeeds in clarifying our knowledge or insight into a system or an object. Weinberg (1975) defined a model as the "expression of one thing we think we hope to understand in terms of another that we think we do understand."

Understanding the world of modeling is essential before using the model to predict the future of a system or an object. Bender (1978) suggests that a model is a summary of a world which consists of three things: (1) "things whose effects are neglected, (2) things that affect the model but whose behavior the model is not designed to study, and (3) things the model is designed to study the behavior of." Once a physical law is understood by human beings, attempts will be made to formulate that law into some mathematical expressions. Mathematical modeling, or abstract modeling, is a model that uses mathematical expressions as a shorthand, or a language, to describe a system or an object. In Bender's words "mathematical modeling is neither science nor math but how to put them together."

Mathematical modeling for border irrigation started as early as the 1960's. The early models were intended to deal with only a portion of the irrigation process so that the validity of certain equations or solution techniques could be tested. For instance, Shih (1966) proposed a model which was used to explain the advance portion of the irrigation

process. Subsequent models were built to describe the complete irrigation process (Fangmeter et al.. 1979). These recent models can quickly, reliably, and economically evaluate the performance of the border irrigation system. These models can also be used to elucidate the mechanism of border irrigation hydraulics. The theory of available models are discussed in the following sections.

The Theory of Available Models

The full hydrodynamic, zero-inertia, and kinematic-wave models are the three available mathematical models which have been developed for surface irrigation. Zero-inertia, and kinematic-wave models have been specifically used for border irrigation application. All mathematical models for surface irrigation use a volume balance or the continuity equation and they can differ from one another in the choice of the motion equation (Jensen, 1983).

Full Hydrodynamic Model

The full hydrodynamic model is perhaps the oldest model developed for border irrigation. This model utilizes the laws of conservation of mass in addition to Newton's second law (conservation of momentum) to characterize the gradually varied unsteady flow in border irrigation.

The Saint-Venant equations (Figure 5) are the laws of conservation of mass and momentum expressed in partial differential equations to describe the nonuniform surface water flow in border irrigation (Chow. 1959; Henderson,

1966; and Strelkoff. 1969).

Figure 5. Definition sketch of Saint-Venant equations for a
flow element.

The equation of mass-conservation in Figure 5 can be
expressed in terms of the continuity equation as follows.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial X} + I = 0 \qquad (3.1)$$

where

A= cross-sectional area at the middle of the flow element,
L^2.

Q= discharge, L^3/T.

I= volumetric rate of infiltration per unit length of
channel, L^3/TxL.

x= distance from the upper end of the channel, L.

t= time, T.

The equation of momentum-conservation in Figure 5 can be
expressed in terms of the equation of motion (Newton's

second law) as follows.

$$\frac{1}{g}\frac{\partial V}{\partial t} + \frac{V}{g}\frac{\partial V}{\partial X} + \frac{\partial y}{\partial X} = S_o - S_f + \frac{IV}{2Ag} \qquad (3.2)$$

where

g= acceleration of gravity, L/T^2.

V= Q/A or mean velocity parallel to the channel, L/T.

y= flow depth normal to channel bottom, L.

S_o= channel bottom slope, L/L.

S_f= energy gradient or channel friction slope, L/L.

The following assumptions must be made in order to derive equations (3.1) and (3.2).

1) Water density is constant. This means that the equation (3.1) can be treated as volume-conservation.

2) Flow is one dimensional in direction of slope.

3) Momentum coefficient is unity. That is, the pressure distribution normal to the channel bottom is hydrostatic and the flow is parallel to the channel bottom.

4) Energy coefficient is unity. That is. the velocity distribution at each cross section is uniform but drops to zero at the channel walls.

5) Channel's bottom slope is small so that the flow depth in the vertical direction is approximately equal to the depth normal to the channel bottom.

6) Resistance forces to flow created by the soil surface and vegetation are a function of flow depth and velocity as if the flow were steady and uniform.

Strelkoff (1970) stated that the inaccuracy in the estimation of flow caused by the above assumptions would be much less than those caused by imprecise specification of

infiltration and/or hydraulic roughness.

The equations (3.1) and (3.2) constitute a pair of first order partial differential equations with independent variables x and t, and dependent variables Y and V. Crandall (1959) has shown that equations (3.1) and (3.2) can be classified as hyperbolic equations. Although hyperbolic equations can be solved numerically using finite-difference methods, they are normally dealt with by using the method of characteristics. The method of characteristics first finds special curves in the x-t plane (characteristic curves) along which the solution of the partial differential equations is reduced to the integration of ordinary differential equations. The ordinary differential equation then is integrated using numerical methods (Smith, 1978).

Bassett et al. (1976) and Katopodes et al. (1977) presented full hydrodynamic models using the method of characteristics to solve equations (3.1) and (3.2). The results of these models made it possible to regard them as standards against which the recent models can be compared.

Zero-Inertia Model

The first zero-inertia model for a complete border irrigation process was presented by Strelkoff et al. (1977). The zero-inertia model is a simplified version of the full hydrodynamic model with good accuracy and a much lower computational cost.

The theory behind the zero-inertia model is that since the change in depths and velocities are very small for border irrigation, all inertial (acceleration) terms in equation (3.2) can be neglected. The equation (3.2) then becomes:

$$\frac{\partial y}{\partial x} = S_o - S_f \tag{3.3}$$

Strelkoff et al. (1977) supported the fact that for low velocities, or Froud numbers below 0.3, the forces acting on the surface stream are in balance independent of the acceleration terms in equation (3.2). The surface stream flow can be analyzed by dividing the stream length into a number of cells. A single water cell is shown in Figure 6.

Figure 6. A single water cell with moving faces.

where

X_{u1}, X_{d1}, = are the location of the upstream and downstream
X_{u2}, X_{d2} surfaces the cell at the beginning and the
            end of the time step Δt.

Y_{u1}, Y_{d1}, = are the depth of the surface water at the
Y_{u2}, Y_{d2} upstream and downstream surfaces of the cell
            at the beginning and the end of the time step Δt.

Z_{u1}, Z_{d1}, = are the depth of the infiltrated water at the
Z_{u2}. Z_{d2} upstream and downstream surfaces of the cell
            at the beginning and the of the time step Δt.

Q_{u1}, Q_{d1}, = are the flow in and flow out of the cell at
Q_{u2}, Q_{d2} the beginning and the end of the time step Δt.

The cells must be selected so that variation of depth and

discharge over the length of a cell can be assumed to be

linear. As the water cell moves for a time period Δt, the

computation network in the x-t plane can be presented as in

Figure 7.

Figure 7. Computation network in the x-t plane.

The advance curve can be drawn by connecting the X_{df} points in Figure 7 (final locations of the downstream faces of the cell for the last time period Δt).

The equilibrium of the forces on surface-water can be shown as in Figure 8.

Figure 8. Equilibrium of forces on surface-water cell.

where

$P_u-P_d=$ are the hydrostatic pressures extended by water in the neighboring cells upstream and downstream from the given cell.

W = is the downstream component of the weight.

D = is the drag force caused by vegetation as well as the soil surface.

In equation (3.3), the net result of the hydrostatic pressure (P_u-P_d) is represented by $\dfrac{\partial y}{\partial x}$ while W and D are represented by S_f and S_d respectivly.

The zero-inertia model uses a numerical solution for equations (3.1) and (3.3) using the method of characteristics. This model is commonly used today because of its low computational cost and its adaptibility to digital computers.

Kinematic-Wave Model

Kinematic-wave theory was first studied for border irrigation by Smith (1972). In this model the bottom slope is assumed to be relatively large causing uniform flow with normal depth at every point along the stream. That is, in Figure 8, the downstream component of the weight (W) and the drag force (D) are much larger than the net result of the hydrostatic pressure (P_u-P_d). The net result of the hydrostatic pressure can, therefore, be neglected. The equation (3.3) then becomes:

$$S_o - S_f = 0 \qquad (3.4)$$

or

$$S_o = S_f \qquad (3.5)$$

The kinematic-wave model reduces equations (3.1) and (3.5) to a pair of ordinary differential equations and then solves them numerically using the method of characteristics.

It should be noted that the kinematic-wave model fails where the horizontal bottom slope is encountered. Equation (3.5) is also not satisfied for the regions where depth

gradient is large such as the front edge of the advancing stream.

Selecting an Appropriate Model

The "BRDRFLW: A Mathematical Model of Border Irrigation" by Strelkoff (1985) has been selected to test for surge flow border irrigation. The BRDRFLW is a software program written in Fortran. The model predicts the behavior of the flowing surface water in border irrigation. The Strelkoff's BRDRFLW model has been selected for the following reasons:

1) The model is the latest available model in the market which could describe the complete process of border irrigation.

2) The running version of the model is available economically in a floppy disc which could be used with almost any computer.

3) The model uses both zero-inertia and kinematic-wave options and therefore was flexible to suit any particular condition in border irrigation.

4) The model is far less complicated than the full hydrodynamic models.

The model assumes infiltration to be only a function of time. The equation for infiltration which is presented in BRDRFLW is as follows.

$$Z = Kt^A + Bt + C \qquad (3.6)$$

where

Z = accumulated intake.

t = intake opportunity time.

K, A, B, and C = constants to classify a particular soil.

The input information (exogenous variables) for the model were two kinds, the physical characteristics of the border being irrigated and management parameters. The physical characteristics input are:

1) border length
2) slope
3) roughness
4) downstream boundary condition, is the stream free to drain out of the border or blocked by an end check
5) soil infiltration characteristics

The management parameters are:

1) required depth of application
2) inflow rate
3) cutoff time

The exogenous variables for the model can be expressed in metric, English, or dimensionless units.

Once the exogenous variables are entered in the model. the computer program can select either the zero-inertia or kinematic-wave options to solve output variables (endogenous variables). The endogenous variables are:

1) advance as a function of time
2) recession as a function of time
3) percent runoff (applied volume/runoff volume)
4) ultimate distribution of applied water
5) distribution and application efficiency

All endogenous variables then would be printed out by the BRDRFLW model in metric, English. and dimensionless units.

Calibration of the Model

An irrigational problem was idealized in an effort to calibrate the Strelkoff's BRDRFLW model. The crop was assumed to be alfalfa with a roughness coefficient of 0.15 as suggested by the U.S. SCS (1974). The soil was assumed to

be silty loam with K, A, B, and C to be 4.68, 0.547, 0.0, and 0.0 respectively (Merriam et al., 1985). The border length was selected as 100 m with a slope of 0.3% (Melvyn, 1986). The boundary condition at the end of the border was assumed to be open to runoff. Melvyn (1986) suggests an inflow of 7 l/s.m for silty loam soils with a corresponding 10 cm soil moisture deficiency. The cutoff time was approximated as 15 minutes. A summary of all exogenous variables explained above is presented in the Table 3.

Table 3. Exogenous data for calibration of the model.

Exogenous Variables	Physical Characteristics	Management Parameters
Roughness	0.15	
Soil Infiltration Characteristics, K	4.68	
A	0.547	
B	0.0	
C	0.0	
Border Length	100 m	
Slope	0.3%	
Downstream Boundary Condition	Open for Runoff	
Required Depth of Application		10 cm
Inflow Rate		7 l/s.m
Cutoff Time		15 min.

Once the exogenous data were provided for the BRDRFLW model, the model was calibrated for endogenous variables using the zero-inertia and the kinematic-wave options. Table 4 shows three of the endogenous variables, the distribution efficiency, the application efficiency, and the percent runoff generated by the zero-inertia and the kinematic-wave options.

Table 4. The endogenous variables generated by the model.

Endogenous Variables	Zero-Inertia Model	Kinematic-Wave Model
Distribution Efficiency	37.64%	33.30%
Application Efficiency	59.75%	52.86%
Percent Runoff	39.75%	47.54%

The advance and recession curves generated by the zero-inertia and kinematic-wave options are plotted in Figure 9. In Figure 9 it can be seen that for the same input information the zero-inertia and the kinematic-wave options generated similar advance curves but different recession curves. The recession curve generated by the kinematic-wave option used the cutoff time as a starting point for recession to occur and didn't include the lag time. The zero-inertia option, on the other hand, used the lag time but created a recession curve which wasn't as smooth as the curve created by the kinematic-wave option. Figure 10 shows

Figure 9. The advance and recession curves produced by the model.

Figure 10. The ultimate distribution of applied water produced by the model.

the ultimate distribution of applied water which was produced by the zero-inertia and kinematic-wave options. Figure 10 shows that, under the same input information, the zero-inertia options allows more infiltration than the kinematic-wave option. Since the input information was selected arbitrarily, no conclusion could be drawn as to which option was more reliable.

The calibration of the BRDRFLW model was conducted with no complications except that the model required a computer running time of 45 minutes before any output could be generated. A Mathcoprocessor in the computer's main library, would have allowed the model to run much faster. Samples of the complete information generated by the BRDRFLW model are presented in Appendix B (Figure 29).

Testing of the Model

Actual field data presented by Merriam et al. (1978) were used to test the BRDRFLW model(Appendix C). Table 5 shows a summary of all exogenous variables needed for running the BRDRFLW model.

Table 5. Exogenous data from Merriam et al. (1978).

Exogenous Variables	Physical Characteristics	Management Parameters
Crop	Alfalfa	
Soil	Sandy Loam	
Border Length	259 m	

Table 5. Continued.

Exogenous Variables	Physical Characteristics	Management Parameters
Slope	0.5%	
Downstream Boundary Condition	Open for runoff	
Required Depth of Application		7.4 cm
Inflow Rate		5.3 l/s.m
Cutoff Time		88 min.

Roughness and soil infiltration characteristics are the two variables which can't be measured as precisely as other exogenous variables, and therefore must be estimated. The roughness is a function of crop and soil resistance to flow. Knowing the crop to be alfalfa and the soil to be sandy loam, the U.S. SCS (1974) suggests a roughness value ranging from 0.15 to 0.25. A value of 0.25 for roughness represents a condition where dense alfalfa is seeded across the border with a rough soil surface. The soil infiltration characteristics can be either computed using an adjusted infiltration evaluation (Appendix D) or they can be estimated using U.S. SCS (1974) or Merriam et al. (1985) sources.

In order to check the model's sensitivity against roughness or soil infiltration characteristics, two kinds of tests were conducted using the zero-inertia option of the

BRDRFLW model. For each series of tests, if any erratic perturbation in advance and recession curves were observed, the model would have been believed to be sensitive.

In the first series of tests, all exogenous variables were held constant except the roughness coefficient which was assigned values of 0.1,0.15, 0.2 and 0.25 (Figure 11).

Figure 11. Model's sensitivity variation in the coefficient of roughness using the zero-inertia option.

Figure 11 shows that the advance curve is less sensitive to the change in roughness than the recession curve. Because of an abrupt perturbation in the recession curve due to a slight variation in roughness values, the model was believed to be sensitive to the changing roughness values. The kinematic-wave option confirms that the BRDRFLW model is

sensitive to changing roughness values because of an abrupt
perturbation in recession curves (Figure 12).

Figure 12. Model's sensitivity variation in the coefficient
of roughness using the kinematic-wave option.

Since the kinematic-wave option introduces the same effect
as the zero-inertia option, the remaining tests were
conducted using only the zero-inertia option.

In the second series of tests, all variables were held
constant except soil infiltration characteristics. The
values assigned to soil infiltration characteristics were
all selected from the same source and varied only within a
range representing sandy loam. This range was identified in
Figure 13 as being low, medium, and high. Figure 13
indicates that the model is also sensitive to soil
infiltration characteristics since the recession curve

changed abruptly with changes in infiltration.

Figure 13. Model's sensitivity to soil infiltration characteristics.

Due to the sensitivity of the model, the roughness and soil infiltration characteristics must be selected carefully.

The next step was an examination of the reliability of information sources for soil infiltration characteristics. These were the computational method, the U.S. SCS (1974), and Merriam et al. (1978). Table 6 shows that each source describes a sandy loam soil differently. Three tests were conducted using the zero-inertia option of the BRDRFLW model. Each test used a different source of information as presented in Table 6 to generate advance and recession curves.

Table 6. Soil infiltration characteristics describing
sandy loam by different sources.

Sources	Soil Infiltration Characteristics	K	A	B	C
U.S. SCS (1974)		0.108	0.808	0.0	0.275
Merriam et al. (1985)		8.28	0.643	0.0	0.0
ComputationalMethod		0.447	0.664	0.0	0.232

The results generated by the computations were compared to
the actual data prepared by Merriam et al. (1978) as
depicted in Figure 14.

Figure 14. The comparison of the advance and recession
curves produced by the model to actual data.

From Figure 14 it can be seen that the Merriam et al.
(1978) data is close to the actual condition for describing

the soil infiltration characteristics. The model produced advance and recession curves similar to the actual field data. Clemmens (1981) studied different methods for evaluating the infiltration measurements and concluded that U.S. SCS (1974) data was inadequate and did not correspond the actual infiltration characteristics for most soils. The sealing effect in the ring infiltrometer, used by the U.S. SCS (1974) and the computational method, was determined to be the main source of error. Merriam et al. (1985) then developed a new family of intake curves based on how long the water must be on the field to infiltrate 100 mm.

Figure 15. Best results produced by the BRDRFLW model.

Figure 15 was the next attempt to reproduce the actual field data in Appendix C by assigning different values to

roughness and soil infiltration characteristics. A roughness of 0.25, K of 3.31. and A of 0.643 produced the closest advance and recession curve to that of the actual field data. Figure 15 also shows that the zero-inertia option produces better results than the kinematic-wave option. A roughness of 0.25 was the highest value suggested by U.S. SCS (1974).

Figure 16 is provided to compare the actual infiltration profile through the soil (Table 15, Appendix C) with the infiltration profiles created by the model.

Figure 16. The infiltration profile created by the model compared to the actual field data.

From Figure 16 it can be seen that both the zero-inertia and kinematic-wave options allowed deeper infiltration than the

actual field data. The zero-inertia option is probably more reliable for design purposes to avoid any area of under-irrigation.

It should be mentioned here that the BRDRFLW model contained an option called the "hybrid" option which utilized the zero-inertia option to produce an advance curve and the kinematic-wave option to produce the recession curve. This option, however, could not be used because of the error messages which could not be explained.

The knowledge which has been extracted from testing the BRDRFLW model can be summarized as follows.

1) The model is sensitive to both roughness and soil infiltration characteristics, especially the recession curves. The values to be assigned to these variables must be selected meticulously.

2) Merriam et al. (1978) is the most reliable source to represent soil infiltration characteristics.

3) The BRDRFLW's zero-inertia option produces more reliable results by allowing deeper infiltration and considering the lag time before recession.

4) The roughness values used for the model tend tobe higher than those suggested by U.S. SCS (1974).

CHAPTER 4

FIELD TESTING

The time for water advance and recession for three border strips was evaluated at the Fort Keogh Livestock and Range Research Station located at Miles City, Montana. Three side by side border strips were selected so that water could be conveniently guided from one border to another. Two of the border strips were for surge flow irrigation and one was for conventional continuous flow irrigation. The SCS Irrigation Guide of the State of Montana defined the soil's composition as clayey loam with very slow permeability and moderate available water holding capacity. The expected surface runoff was medium and the erosion hazard moderate. The crop was sixth year alfalfa, and it was being irrigated for the second time. The alfalfa was short enough that the water advance and recession could easily be observed.

The borders were all 15 m in wide and 427 m long. The border's transverse slope was zero and the slope in the direction of irrigation had been graded to 0.2% for the first 244 m, 0.3% for the next 122 m, and 0.5% for the last 91 m. These changes in the slope along the border had been made to attenuate the deep percolation at the middle of the

border strip.

The general procedure for advance and recession evaluation described by Merriam et al. (1978) was closely followed. The following materials were used to perform the advance and recession analysis for surge flow and conventional continuous flow border irrigation:

lath	digital watch
fluorescent flagging	soil bags
measuring tape	soil auger
soil probe	field notebook and pen
hatchet	calculator

The length of the border strip was measured and a lath was installed every 30 m to indicate a single station. These stations were selected so that one set of laths along the strip could be used for all three borders. Every fifth station was designated by fluorescent flagging to aid in field readings.

Soil samples were taken and soil textures were examined to determine the uniformity of the soil along the border. The soil texture was found to be fairly uniform throughout the borders. In a few small areas the growing alfalfa was immature compared to surrounding areas in the borders. The immaturity of alfalfa was believed to be caused by the clayey soil with extremely low permeability which accumulated salt during six years of irrigation.

The next step was to measure the soil moisture deficiency to determine how much water should be applied. Merriam (1960) approximated the relationship between field

capacity and wilting point as a function of the soil moisture and provided a chart to indicate the soil moisture deficiency by describing the soil texture. The soil in the borders was found to be quite dark and easily slicked and a thick ribbon could be easily formed indicating a soil moisture deficiency of approximately 140 mm in the root zone.

The water flow rates were measured with a flow meter installed on the main pipe outlet. The flow rate for conventional continuous flow and the two surge flow border was 57 l/s. This flow rate was constant throughout the irrigation period.

After preliminary work was completed, the surge flow irrigation was begun by opening the headgate to start the first surge in the first border. The starting time was recorded and as water advanced down the first border, the arrival time at each station was registered. Judging the advance front was difficult since it was not uniform transversely across the border. The flow was changed to an adjacent border once the predetermined surge time had elapsed. This time was recorded separately.

The recession time was then recorded for each station on the first border. At the same time, the advance time was being registered for the first surge on the second border. The flow of water was changed to the first border strip to start the second surge once the predetermined surge time had

elapsed. The recession time was recorded for each station on the second border strip. This procedure was iterated for three surge cycles until the irrigation was complete. The advance and recession data are presented in Appendix A (Tables 8 and 9). Figure 17 shows the advance and recession curves for surge flow on the first border.

Figure17. Advance and Recession curves for surge flow on border no. 1.

The water was shut off for the surge flow irrigation when the advance front reached approximately three-fourths of the border length. This practice minimized runoff from these borders. The same practice was used to run the surge flow on the second border (Figure 18).

Figure 19 shows the advance and recession curve for conventional border irrigation.

Figure18. Advance and recession curves for surge flow on border no. 2.

Figure 19. Advance and recession curve for conventional flow on border no. 3.

The complete advance and recession data for conventional continuous flow are presented in Appendix A (Table 10).

The depth of the infiltration was measured using a soil probe at alternate stations 24 hours before and after the irrigation. The differences between the depth of infiltration before and after irrigation were recorded and the results presented in Appendix A (Table 11). The soil probe indicated an average infiltration depth of 140 mm for conventional continuous flow and 154 mm for surge flow.

Difficulties in Field Observation

Several difficulties were encountered during the field observation. A description of these problems and the strategies used to ameliorate them are as follows.

The borders at the Fort Keogh Livestock and Range Research Station were six years old and the border ridges had deteriorated. A tremendous time and effort was needed to reconstruct the deteriorated sections of the border ridges before irrigation to insure that no water leaked from one border to another. During irrigation more leaks developed which were caused by animal tunnels. These tunnels could not be filled. Shoveling the soil around these tunnels prevented water leakage but caused an aberration in the water advance front. A bad leak was noticed during the conventional border irrigation. This leak occured at about three-fourths of the border length (Appendix A, Table 10, at station 3+35). Although the leakage was controlled, the

advance data for the remaining four stations were unreliable. To adequately irrigate the last four stations the inflow was not shut off until the advance front approached the end of the border strip. This practice caused some runoff.

A precise determination of the advance front was difficult due to the broad width of the border. The advance front did not follow a well-defined straight line across the border for a particular station. For some stations, one side of the advance front lagged behind the other side by as much as 30 m. If three-fourths of the advance front crossed a particular station, the time was recorded as the advance time for that station. The same kind of judgment was made for all stations.

The clay soil with extremely low permeability made the recession measurements nebulous. At the same station, water remained impounded in some areas and infiltrated completely in others. Again, a personal judgment was made. If approximately three-fourths of the water infiltrated across a particular station, recession was considered to have occurred. Before water completely disappeared from the soil surface, the recession occured both upstream and downstream simultaneously. Since there was only one person available to record the advance or recession data, a complete set of data for all stations were not possible and many data as a result are missing.

ANALYSIS OF FIELD DATA

The advance and recession curves for the two surge flow borders and the conventional flow border are shown in Figures 17, 18, and 19. With surge flow. three surges were required to finish the irrigation. A time of one hour was selected for the first cycle. This time was extended to an hour and half for the last two cycles. Since the lag time was long, due to the soil's slow permeability. the additional half hour was necessary to provide an opportunity for the water to recede.

As shown in Figures 17 and 18, the advance curves for each subsequent surge flattened. Westesen et al. (1986) interpreted this flattening as an augmentation of the velocity of the advance front for the second and third surges of water.

Faster advance with surge flow resulted in less deep percolation at the upper end of the border. This is verified by probe measurements of the average infiltration depth of 182 mm for the conventional method and 154 mm for surge method (Appendix A, Table 11).

The total time of application for the conventional method was 6 hours and 40 minutes. This time was only 4 hours for surged borders. This time difference indicates that with surge flow irrigation about 2/3 as much water was needed for water to advance to the end of the border as compared to conventional continuous flow irrigation.

The application efficiency for each method of irrigation could be determined by comparing the soil moisture deficiency to the average depth of application. The average depths of application, were 182 mm for conventional continuous flow and 154 mm for surge flow. With a soil moisture deficiency of 140 mm, the application efficiencies were 77% for conventional continuous flow but 91% for surge flow. It should be noticed, however, that the efficiencies reported above take into consideration the deep percolation losses and neglect the runoff losses. Adding the runoff losses to the deep percolation losses, the efficiencies reported above would be lower. But since the efficiencies are compared under the same circumstances, it can be said that the surface irrigation, under at least some conditions, can be substantially improved using surge flow irrigation.

CHAPTER 5

MODEL APPLICATION TO SURGE FLOW TEST RESULTS

Data Preparation

The roughness coefficient and soil infiltration characteristics had to be estimated in order to run the BRDRFLW model for the surge flow border irrigation tests. As mentioned in Chapter 3, the roughness values tended to be higher than those suggested by U.S. SCS (1974). Since the crop was alfalfa and the borders were old and deteriorated, it was reasonable to assume a roughness value of 0.25. The model was run for the tested conventional continuous flow irrigation (Table 10, Appendix A) in an effort to estimate the infiltration characteristics of the soil. If the model could produce the same advance and recession curve as those tested in the field using the conventional continuous flow, the soil infiltration characteristics would account for the behavior of the soil. The method proposed by Merriam et al. (1985) was used to define the infiltration characteristics of the clay soil tested in the field. The zero-inertia option of the BRDRFLW model was used for several values defining the clay soil. The model could not accept the three different slopes which were designed into

the border. The model generated error messages that error
could not be explained. An average value of 0.3% therefore
had to be used. This average slope caused no problem, and
the model generated an advance and recession curve similar
to the field data. Table 7 shows the exogenous variables
supplied to the model to generate a similar advance and
recession curve to that shown in Figure 19 (Chapter 4).

Table 7. Exogenous variables provided for the model to
reproduce Figure 19 (Chapter 4).

Exogenous Variables	Physical Characteristics	Management Parameters
Roughness	0.25	
Soil Infiltration Characteristics, K	5.61	
A	0.58	
B	0.0	
C	0.0	
Border Length	427 m	
Slope	0.3%	
Downstream Boundary Condition	Open for Runoff	
Required Depth of Application		140 cm
Inflow Rate		4.2 l/s.m
Cutoff Time		400 min.

Figure 20 compares the advance and recession curves
generated by the model, Table 7, to the curves measured in
the field data (Table 10, Appendix A).

Figure 20. Advance and recession curves generated by the model compared to conventional continuous flow data.

As can be seen from Figure 20, the results are very similar and therefore the values of K equal to 5.61 and A equal to 0.58 appear to define the infiltration characteristics of the soil.

Figure 21 shown to compare the infiltration profiles generated by the model to those measured in the field for conventional continuous flow (Table 11, Appendix A). Figure 21 indicates that the measured infiltrated depth was slightly higher than the infiltrated depth generated by the model. These differences were small and can be neglected without jeopardizing the accuracy of the model.

Figure 21. Infiltration profile generated by the model compared to measured field data.

Once the model's results were shown to compared reasonably to the actual data for conventional continuous irrigation, all exogenous variables in Table 7 were prepared to be tested for surge flow border irrigation.

Analysis of Results

The soil infiltration characteristics had to be determined as the first step before the model could be used for surge flow border irrigation. The soil infiltration characteristics for the first surge were the same as for conventional continuous flow since no surface sealing had yet occurred. Once the cutoff time changed to 60 minutes, the same exogenous variables in Table 1 were used to run the model for the first surge. Figures 22 and 23 are provided to

illustrate the advance and recession curve generated by the model for the first surge compared to the actual field data (Tables 8 and 9, Appendix A).

Figure 22. Advance and recession curve generated by the model for the first surge compared to the field data (Table 8, Appendix A).

As shown in Figures 22 and 23, the model produces an advance and recession curve similar to the actual field data. One advantage of using the model was that it completed the missing data which could not be obtained in field situations. Point A in Figure 22 and point B in Figure 23 are the results of complete information provided by the model which indicated that the first surge of water wetted the soil surface up to 200 m along the border. The soil within this 200 m of the border then was sealed, but the

remaining 227 m of the border contained soil which was dry and not sealed yet.

Figure 23. Advance and recession curve generated by the model for the first surge compared to the field data (Table 9, Appendix A).

Once the model's results for the first surge were determined to be satisfactory, the second step was to check the reaction of the model for the second surge. In the second surge on the same border, there were two kinds of soil to deal with, the sealed soil and dry soil. The soil infiltration characteristics in Table 7 were the same as for the dry soil. However, a new infiltration characteristic had to be developed for the first 200 m of the border to account for the characteristics of the sealed soil. The most natural choice to define the sealing effects on the soil was

to select higher percent clay soil (soils with slower infiltration rates). Work by Merriam et al. (1985) was used to define the soils' lower infiltration rates. The model then was used to generate the second advance and recession curve for the first 200 m of the border where soil was sealed. Even with the highest percent clay soil as defined by Merriam et al. (1985), the changes in the advance and recession curve were not enough to compensate for the sealing effect (Figure 24).

Figure 24. Advance and recession curve generated by the model for the second surge using the characteristics of the highest percent clay soil.

The roughness value in addition to the soil infiltration rates was changed to compensate for the surface sealing effects. A roughness value of 0.05, K of 1.25, and A

of 0.419 were used for the model to produce the closest fit
of the advance and recession curves to that of the actual
field data (Section P in Figure 25).

Figure 25. The best advance and recession curve generated by
the model for the second surge as compared to the
field data.

In Figure 25, data from Table 7 (conventional irrigation)
was used for the remaining 227 m where the soil surface was
dry and not yet sealed (Section S). Figure 25 shows that
the roughness value should be reduced in addition to
reduction in the soil infiltration rate in order to
compensate for the changes in the soil surface due to the
sealing effect. The fact that the roughness value had to be
reduced to explain the surface sealing of the soil, was an
important result extracted from the model. Most of the

previous studies in surface sealing focused on the reduction
of the soil infiltration rate as the major factor to explain
the sealing effect. However, more data were needed to
confirm the model's suggestion that roughness also had to be
changed to compensate for the surface sealing effects.
Finally, it can be seen from Figure 25 that the second
surge of the water arrived at the end of the border and
wetted the entire soil surface along the border.

At this point there were no guidelines as to how much the
roughness value or soil infiltration characteristics must be
changed to compensate for the sealing effects. Complete
field data can be taken for surge flow border irrigation
using the typical soils as defined by Merriam et al. (1985).
Using these data, the BRDRFLW model can be run to study the
sealing effects on the soil surface. The results of such a
study can be summarized as a rule of thumb that can be used
for design purposes.

Once the model was adjusted to produce satisfactory
results, the last step was to check the model for the third
surge to see if a similar advance and recession curve could
be generated and compared to field data (Table 8, Appendix
A). Since the second surge delivered the water to the end of
the border, the soil along the entire border was sealed.

A new roughness value and soil infiltration
characteristics had to be developed for the third surge. The
soil was even more sealed for the third surge. A roughness

value of 0.03, K of 1.17, and A of 0.335 produced   results
closest   to that of the actual field data (Figure 26).

Figure 26. Advance and recession curve generated by the
            model for the third surge as compared to the
            field data.

Figure 26 shows a similar advance and recession curve
generated by the model and compared to the actual data for
the third surge. Figure 27 shows all three surges produced
by the model while Figure 28 compares the infiltration
profile produced by the model to the field data (Table 11,
Appendix A). In Figure 28 there are a few centimeters of
discrepency between the model's output and that of the
actual data, but this discrepency is small enough for the
model to remain adequate.

Figure 27. Model's output for surge flow border irrigation.

Figure 28. Infiltration profile comparing the field data and the model's output.

The following steps summarize the BRDRFLW model's approach for designing surge flow border irrigation once the exogenous variables are prepared for the model:

1) The U.S. SCS (1974) can be used for choosing a roughness value while Merriam et al. (1985) canbe used to define the soil infiltration characteristics.

2) The first surge can be run by the model using the information prepared in step 1. From this step it can be discerned how much of the soil is sealed along the border and how much of the soil remains dry.

3) The second surge can be determined by running the model twice: First, running the model for the soil infiltration characteristics and roughness value for thewetted areas: Second,runningthe model for the dry areas using the same information in step 1.

4) From step 3 the model can predict whether the water is advanced to the end of the border or not. If water is not advanced to the end of the border, the third surge would be necessary, otherwise, the second surge might be sufficient for irrigation.

5) The last step is to check the infiltration profile to seeif adequate water has infiltrated. More surges of water or longer time cycles can be used if infiltration depth is decided to be inadequate.

Once the above five steps were taken, the different combinations of number of surges and/or cycle time can be studied to provide the highest efficiency for surge flow border irrigation.

Suggested Modifications

The BRDRFLW model was designed for conventional continuous application of border irrigation. It is possible. however, to use the BRDRFLW model for surge flow border irrigation design but this involves a bookeeping process to determine the changes in flow characteristics and is,

therefore, time consuming. In order to modify the BRDRFLW model for surge flow application, the following changes in the model's software are necessary:

1) The BRDRFLW program should allow more than one soil infiltration characteristic and roughness value so that different soil types can be identified at different sections along the border strip.

2) The BRDRFLW program should allow for several runs at once, each run representing a single surge.

3) The BRDRFLW program should allow a single output representing the complete surge flow border irrigation process by adding the results of each surge into one accumulated result.

Theseg changes in the BRDRFLW model's software were not included in this study but the three suggested modifications are recommended for future work. These changes are needed to use the BRDRFLW model for surge flow border irrigation.

CHAPTER 6

CONCLUSIONS

The BRDRFLW model shows promise in terms of its ability to predict a complete process of the surge flow border irrigation. The zero-inertia option of the BRDRFLW model generated better results than the kinematic-wave option because it included the lag time for the recession curve. The third option of the model which was a hybrid of zero-inertia and kinematic-wave could not be used since the model produced error messages that could not be solved. However, the results of this study should be interpreted carefully since the tested model's calibration was based on limited field data. More field data is required to summarize the results of the model into the guidelines that could confidently be used for design purposes.

The model's software had to be modified for the surge flow border irrigation. Some suggestions have been made as to how the model could be modified for surge flow border irrigation. Once these modifications are made, the BRDRFLW model can be used effectively as a design tool to predict the best combination of cycle time and the number of surges for the most efficient surge flow border irrigation.

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APPENDICES

APPENDIX A

Field Data

Table 8. Advance and recession time for border no. 1.

Station	Advance Time (min.)			Recession Time (min.)		
(meters)	Watch	Diff.	Cumu.	Watch	Diff.	Cumu.
0+00	6:46	1	1	7:59	14	74
0+30	7:00	14	15	8:23	24	98
0+61	7:16	16	31	8:41	18	116
0+91	7:30	14	45	9:03	22	138
1+28	7:44	14	59			
Surge #1	On 6:45		Off 7:45			
0+00	9:19	1	247	11:00	25	348
0+30	9:25	6	253	11:17	17	365
0+61	9:31	6	259	11:33	16	381
0+91	9:37	6	265	11:49	16	397
1+28	9:43	6	271	12:08	17	414
1+52	9:50	7	278			
1+82	9:56	6	284			
2+13	10:05	9	293			
2+43	10:18	13	306			
2+73	10:32	14	320			
3+05	10:55	23	343			
3+35	11:17	22	365			
3+65	11:48	26	391			
Surge #2	On 9:18		Off 10:48			
0+00	12:20	1	506	14:09	20	615
0+30	12:26	6	512	14:28	19	634
0+61	12:32	6	518	14:45	17	651
0+91	12:37	5	523	15:05	20	671
1+28	12:43	6	529			
1+52	12:50	7	536	15:22	17	688
1+82	12:56	6	542	15:36	14	702
2+13	13:01	5	547	15:48	12	714
2+43	13:07	6	553	15:58	10	724
2+73	13:15	8	561	15:55	-3	721
3+05	13:27	12	573	15:49	-6	715
3+35	13:37	10	583			
3+65						
3+96						
4+27						
Surge #3	On 12:19		Off 13:49			

Table 9. Advance and recession time for border no. 2.

Station	Advance Time (min.)			Recession Time (min.)		
(meters)	Watch	Diff.	Cumu.	Watch	Diff.	Cumu.
0+00	7:46	1	1	9:05	20	80
0+30	8:00	14	15	9:25	20	100
0+61	8:15	15	30	9:39	14	124
0+91	8:33	18	48	9:57	18	142
1+28	8:51	18	66	10:11	14	156
Surge #1	On 7:45	Off 8:45				
0+00	10:48	1	315	12:36	28	420
0+30	10:56	6	321	13:07	31	451
0+61	11:02	6	327	13:22	15	466
0+91	11:09	7	334	13:39	17	483
1+28	11:16	7	341			
1+52	11:24	8	349			
1+82	11:32	7	356			
2+13	11:46	14	370			
2+43	12:05	19	389			
2+73	12:25	20	409			
3+05	12:55	30	439			
Surge #2	On 10:47	Off 12:17				
0+00	13:52	1	590	16:01	28	717
0+30	13:58	6	596	16:18	17	764
0+61	14:05	7	603	16:34	16	780
0+91	14:13	8	611	16:50	16	796
1+28	14:19	6	617	16:59	15	811
1+52	14:27	8	625	17:05	12	823
1+82	14:32	5	630	17:17	15	838
2+13	14:39	7	637	17:50	18	856
2+43	14:47	8	645	18:07	17	873
2+73	14:59	12	657	18:02	-5	868
3+05	15:09	10	667	18:00	-2	866
3+35	15:33	24	691	17:57	-3	863
3+65	15:55	20	711			
3+95	16:31	36	747			
4+27						
Surge #3	On 13:51	Off 15:21				

Table 10. Advance and recession time for border no. 3.

Station	Advance Time (min.)			Recession Time (min.)		
(meters)	Watch	Diff.	Cumu.	Watch	Diff.	Cumu.
0+00	7:53	1	1	15:24	27	441
0+30	8:10	17	18	15:45	21	462
0+61	8:29	19	37	16:09	14	476
0+91	8:44	25	62	16:40	31	507
1+28	8:57	13	75	16:56	16	523
1+52	9:13	16	91	17:15	19	542
1+82	9:30	17	108	17:38	23	565
2+13	9:49	19	127	17:53	15	580
2+43	10:01	12	139	18:21	28	608
2+73	10:27	26	165			
3+05	10:47	20	185	18:15	-6	602
3+35	11:39	52	237	18:10	-5	597
3+65	12:35	56	293			
3+96	13:30	55	348			
4+27	14:36	66	414			
Conventional Countinuous Flow				On 7:53	Off 14:57	

Table 11. Infiltration profile for border nos. 1 and 2.

Station	Infiltrated Depth (mm)	
(meters)	Border no. 1 and 2	Border no. 3
0+00	191	202
0+30		
0+61	160	198
0+91		
1+28	162	194
1+52		
1+82	162	186
2+13		
2+43	148	186
2+73		
3+05	146	174
3+35		
3+65	134	165
3+96		
4+27	130	153

APPENDIX B

A Complete Output Generated by the BRDRFLW Model

80

```
*******************************BORDER-IRRIGATION-FLOW PROGRAM***********************
*********

INTERACTIVE USERS -- POSITION PAPER FOR PROMPTS   THEN ENTER (LINE 1)
           1 FOR A FRESH START --
           2 TO CHANGE DESIGN PARAMETERS -- ZREQ,QIN,TCO --
           3 TO CHANGE SOLUTION MODES -- SOLMOD,LINMOD,DTMOD,ISUPZA,ZADMOD --
           4 TO CHANGE SOLUTION PARAMETERS -- NSTD,RDX,DTSTD,TMAX,JMAX --
           5 TO CHANGE LEVEL OF DIAGNOSTICS AND/OR PLOTTING FLAGS --
           0 TO STOP --
1
           1
(LINE 2)............... IDENTIFY THIS RUN ...............
  calibration of the model
  calibration of the model
ENTER (LINE 3) -- INPMOD DMLMOD --
1,1
           1           1
ENTER (LINE 4) SOIL AND CROP HYDRAULIC PROPERTIES --
        RUFMOD RUF AN  INFMOD K A B C --
2,.15,0,1,4.68,.547,0,0
           2 1.500000E-001        .0000000         1    4.6800000
    5.470000E-001        .0000000         .0000000
ENTER (LINE 5) FIELD GEOMETRY -- L DBC SOMOD --


           2 1.500000E-001        .0000000         1    4.6800000
    5.470000E-001        .0000000         .0000000
ENTER (LINE 5) FIELD GEOMETRY -- L DBC SOMOD --
100,1,1
         100.0000000         1         1
ENTER (LINE 6) AVERAGE BOTTOM SLOPE -- SOAVG --
.003
    3.000000E-003
ENTER (LINE 7) MANAGEMENT PARAMETERS -- ZREQ Q TCO --
10,7,15
          10.0000000      7.0000000      15.0000000
ENTER (LINE 9) SOLUTION PARAMETERS -- SOLMOD LINMOD DTMOD ISUPZA ZADMOD --
2,2,0,0,0
           2           2          0          0          0
ENTER (LINE 10) NUMERICAL SOLUTION PARAMETERS -- N(STD) RDX DT(STD) TMAX JMAX -
-
20,1,10,0,0
          20      1.0000000      10.0000000        .0000000
           0
ENTER (LINE 11) DIAGNOSTIC PARAMETERS -- IDIAG IDCH ID2 IPRZA FLGPVE --
0,0,0,0,0
           0           0          0          0        .0000000
ENTER (LINE 12) PLOTTING PARAMETERS -- IPLOTW IPLOTY IPLOTH IPLOTC IPWAIT --

0,0,0,0,0
************************************** B O R D E R   I R R I G A T I O N   F L O W **********************************************

  calibration of the model


                H Y D R A U L I C   P R O P E R T I E S   O F   C R O P   A N D   S O I L
                      D I M E N S I O N E D              D I M E N S I O N L E S S

ROUGHNESS --
MANNING N (COEFFICIENT) = .1500 FT**(1/6)   = .1500 M**(1/6)   EXPONENT = .0000E+00
                                  DIMENSIONLESS DRAG COEFFICIENT   D* = .9999E+00

INTAKE CHARACTERISTICS --            IN INFILTRATION FORMULA  Z = K*T**A + B*T + C  --

        K = 1.8425  IN/HR**A    = 4.6800   CM/HR**A
          = .1962E+00 IN/MIN**A  = .4984E+01 MM/MIN**A
          = .1742E-02 FT/SEC**A  = .5308E-03 M/SEC**A
                                                      K* = .1538E+00
        A = .5470        = .5470              A = .5470
        B = .0000 IN/HR  = .0000 CM/HR       B* = .0000E+00
        C = .0000 IN     = .0000 CM          C* = .0000E+00
```

Figure 29. Computer output.

```
                              B O R D E R   G E O M E T R Y
                              D I M E N S I O N E D                    D I M E N S I O N L E S S

FIELD LENGTH        L = 328.1 FT              = 100.0 M           L* = .3218E+01
AVG. FIELD SLOPE  SOAVG = .0030000            = .3000E-02         SO* = .1000E+01
PLANE SURFACE

OPEN-END BORDER


                    I R R I G A T I O N - M A N A G E M E N T   P A R A M E T E R S
                              D I M E N S I O N E D                    D I M E N S I O N L E S S


REQUIRED APPLICATION   = 3.94 IN             =10.00 CM           ZREQ* = .1073E+01
UNIT INFLOW RATE       = .0753 CFS/FOOT      = 7.000 LITERS/SEC-M  QIN* = .1000E+01
CUT-OFF TIME           = 15.00 MIN           = .250 HR           TCO* = .2174E+01


          C H A R A C T E R I S T I C   P A R A M E T E R S   I N   D I M E N S I O N L E S S   F O R M S

CHARACTERISTIC DEPTH BASED ON NORMAL DEPTH   YO=YN,  XO=YO/SO,  TO=XO*YO/QO

                              D I M E N S I O N E D                    D I M E N S I O N L E S S
NORMAL DEPTH          YN = .3059 FT            = .0932 M               = .1000E+01
FROUDE NUMBER AT NORMAL DEPTH .................................................  FN = .7851E-01
CHARACTERISTIC DEPTH  YO = .3059E+00 FT      = .9324E-01 M
CHARACTERISTIC LENGTH XO = .1020E+03 FT      = .3108E+02 M
CHAR'STIC DISCHARGE   QO = .7535E-01 CFS/FOOT = .7000E+01 LITERS/SEC-M
CHARACTERISTIC TIME   TO = .6900E+01 MIN     = .4140E+03 SEC




                         N U M E R I C A L   S O L U T I O N   P A R A M E T E R S

ZERO-INERTIA (EQUILIBRIUM) SOLUTION
DEPTH AND DISCHARGE FUNCTIONS ARE TREATED AS FULLY NONLINEAR
MAXIMUM ALLOWABLE NUMBER OF ITERATIONS   JMAX = 20
WHEN WATER SURFACE OF COMPUTATIONAL STREAM IS ESSENTIALLY LEVEL, INFILTRATION IS ASSUMED TO BE THAT OF LEVEL POOL(S)

NUMBER OF CELLS IN STREAM = 20
STANDARD TIME STEP    DT = 10.00 MIN         = .167 HR           DT* = .1449E+01
DT=DT(STD)/N(STD) FOR FIRST N(STD) TIME STEPS.  THEN DT GRADUALLY INCREASED TO DT(STD)
                    TMAX =7800.00 MIN        = 130.0 HR          TMAX* = .1130E+04


                         ZERO-INERTIA (EQUILIBRIUM) MODEL


POST-IRRIGATION SYNOPSIS


...................... U L T I M A T E   I N F I L T R A T I O N   P R O F I L E ...................

  K      X         TA        TR        Z        TA MIN   TR MIN   X METERS  Z CM    X FEET   Z IN
  1  .0000E+00  .0000E+00  .3024E+01  .2817E+00      .0    20.9       .0     2.6      .0     1.03
  5  .3218E+00  .2413E+00  .4930E+01  .3580E+00     1.7    34.0     10.0     3.3    32.8     1.31
  9  .6435E+00  .5319E+00  .5998E+01  .3894E+00     3.7    41.4     20.0     3.6    65.6     1.43
 13  .9653E+00  .8508E+00  .6153E+01  .3829E+00     5.9    42.5     30.0     3.6    98.4     1.41
 17  .1287E+01  .1188E+01  .6751E+01  .3931E+00     8.2    46.6     40.0     3.7   131.2     1.44
 21  .1609E+01  .1538E+01  .7864E+01  .4217E+00    10.6    54.3     50.0     3.9   164.0     1.55
 25  .1931E+01  .1898E+01  .8199E+01  .4208E+00    13.1    56.6     60.0     3.9   196.8     1.54
 29  .2252E+01  .2267E+01  .8508E+01  .4186E+00    15.6    58.7     70.0     3.9   229.7     1.54
 33  .2574E+01  .2657E+01  .9451E+01  .4385E+00    18.3    65.2     80.0     4.1   262.5     1.61
 37  .2896E+01  .3051E+01  .9965E+01  .4428E+00    21.0    68.8     90.0     4.1   295.3     1.63
 41  .3218E+01  .3499E+01  .1075E+02  .4543E+00    24.1    74.1    100.0     4.2   328.1     1.67
```

Figure 29. Continued.

82

```
Y MAX    (MAXIMUM DEPTH OF SURFACE STREAM ATTAINED AT ANY POINT) ..............  .30 FOOT   9.19 CM   .9856E+00
X YMAX   (LOCATION OF POINT OF MAXIMUM DEPTH) ...............................  .00 FOOT    .00 M    .0000E+00

Z MIN    (MINIMUM DEPTH OF INFILTRATION) ....................................  1.02 INCH  2.59 CM   .2783E+00   41.2 %
Z MAX    (MAXIMUM DEPTH OF INFILTRATION) ....................................  1.67 INCH  4.24 CM   .4543E+00   67.2 %
Z LQ     (AVERAGE LOW-QUARTER DEPTH OF INFILTRATION) ........................  1.29 INCH  3.28 CM   .3522E+00   52.1 %
Z REQ    (REQUIRED DEPTH OF INFILTRATION) ...................................  3.94 INCH 10.00 CM   .1073E+01  158.7 %

Z Q      (AVERAGE APPLIED DEPTH        VQ/L) ................................  2.48 INCH  6.30 CM   .6757E+00  100.0 %
Z AVG    (AVERAGE INFILTRATED DEPTH    VZ/L) ................................  1.48 INCH  3.76 CM   .4037E+00   59.7 %
Z RO     (AVERAGE DEPTH OF RUNOFF      VRO/L) ...............................   .99 INCH  2.50 CM   .2686E+00   39.7 %

Z DP ZREQ (AVERAGE DEPTH OF DEEP-PERCOLATION VOLUME BASED ON GIVEN REQUIRED DEPTH)  .00 INCH   .00 CM   .0000E+00    .0 %
Z DP ZMIN (AVERAGE DEPTH OF DEEP-PERCOLATION VOLUME BASED ON ZREQ = ZMIN)    .46 INCH  1.17 CM   .1255E+00   18.6 %
Z DP ZLQ  (AVERAGE DEPTH OF DEEP-PERCOLATION VOLUME BASED ON ZREQ = ZLQ)     .20 INCH   .51 CM   .5510E-01    8.2 %
Z U ZREQ  (AVERAGE OF INFILTRATED DEPTHS LESS THAN OR EQUAL TO REQUIRED DEPTH) 1.48 INCH  3.76 CM   .4037E+00   59.7 %
Z U ZMIN  (AVERAGE OF INFILTRATED DEPTHS LESS THAN OR EQUAL TO ZMIN)         1.02 INCH  2.59 CM   .2783E+00   41.2 %
Z U ZLQ   (AVERAGE OF INFILTRATED DEPTHS LESS THAN OR EQUAL TO ZLQ)          1.28 INCH  3.25 CM   .3486E+00   51.6 %

UC C     (CHRISTIANSEN UNIFORMITY COEFFICIENT) ............................................  .924
UC H     (HSPA UNIFORMITY COEFFICIENT) ...................................................  .923
DU       (DISTRIBUTION UNIFORMITY          ZMIN/ZAVG) .....................................  .689
DU LQ    (LOW-QUARTER DISTRIBUTION UNIFORMITY  ZLQ/ZAVG) ..................................  .872
RP       (RUNOFF FRACTION IN PERCENT       VRO/VQ ) .......................................  39.75%
                                                                    BASED ON   BASED ON   BASED ON
                                                                    GIVEN ZREQ ZREQ=ZMIN  ZREQ=ZLQ
IE       (IRRIGATION EFFICIENCY           ZU/ZQ ) ................   59.75%     41.18%    51.59%
UZ       (USEFUL FRACTION OF INFILTRATED VOLUME  ZU/ZAVG) .........   1.000      .689      .864
SE       (STORAGE EFFICIENCY             ZU/ZREQ) .................   37.64%    100.00%    98.99%
AAP      (PERCENT OF TOTAL AREA ADEQUATELY IRRIGATED) ............    .00%     100.00%    91.19%
DR       (DEFICIENCY RATIO, AVERAGE DEFICIT IN UNDERIRRIGATED AREA, PERCENT OF ZREQ) 62.36%       11.52%
```

.... M E A S U R E S   O F   M E R I T   O F   C O M P U T A T I O N ....

```
COMPUTATIONAL VOLUME BALANCE   VQ= .2174E+01   VZ= .1299E+01   VRO= .8641E+00  .......... RELATIVE VOLUME ERROR = .5035E-02
MAXIMUM SIZE OF SAW TEETH IN PROFILES —   ITH= 4  KTH= 2  TOOTHH= .306E+00  IRTH= 37  KRTH= 5  RTOOTH= .178E+01
```

.... S Y N O P S I S   O F   R E S U L T S   O F   I R R I G A T I O N ....

```
                                                                  HOURS    MINUTES  DIMENSIONLESS
T CO     (TIME OF CUT OFF) .............................................   .25    15.00    .2174E+01
T L      (DURATION OF ADVANCE) .........................................   .40    24.14    .3499E+01
T R      (TIME RECESSION STARTS AT UPSTREAM END) .......................   .35    20.86    .3024E+01
T FR     (TIME RECESSION STARTS AT DOWNSTREAM END) .....................  1.24    74.15    .1075E+02
T E      (TIME ALL SURFACE WATER DISAPPEARS) ...........................  1.24    74.15    .1075E+02

                                                                  ENGLISH   METRIC   DIMENSIONLESS
                                                                  FT**3/FT  M**3/M
V Q      (APPLIED VOLUME) ..............................................  67.811    6.300    .2174E+01
V Z      (INFILTRATED VOLUME) ..........................................  40.517    3.764    .1299E+01
V RO     (RUNOFF VOLUME) ...............................................  26.953    2.504    .8641E+00
                                                                                                      % OF
                                                                  ENGLISH   METRIC   DIMENSIONLESS  APPLIED
                                                                                                     DEPTH
Y MAX U  (MAXIMUM DEPTH OF SURFACE STREAM ATTAINED AT UPPER END) .......  .30 FOOT  9.19 CM  .9856E+00
```

Figure 29. Continued

```
*********************************BORDER-IRRIGATION-FLOW PROGRAM*************************
*********

INTERACTIVE USERS -- POSITION PAPER FOR PROMPTS  THEN ENTER (LINE 1)
              1 FOR A FRESH START ---
              2 TO CHANGE DESIGN PARAMETERS -- ZREQ,QIN,TCO ---
              3 TO CHANGE SOLUTION MODES -- SOLMOD,LINMOD,DTMOD,ISUPZA,ZADMOD ---
              4 TO CHANGE SOLUTION PARAMETERS -- NSTD,RDX,DTSTD,TMAX,JMAX ---
              5 TO CHANGE LEVEL OF DIAGNOSTICS AND/OR PLOTTING FLAGS ---
              0 TO STOP ---
1
              1
(LINE 2)............... IDENTIFY THIS RUN ...............
  calibration of model kinematic-wave
  calibration of model kinematic-wave
ENTER (LINE 3) -- INFMOD DMLMOD ---
1,1
              1              1
ENTER (LINE 4) SOIL AND CROP HYDRAULIC PROPERTIES --
      RUFMOD RUF AN  INFMOD K A B C ---
2,.15,0,1,4.68,.547,0,0
              2  1.500000E-001          .0000000              1       4.6800000
    5.470000E-001          .0000000          .0000000
ENTER (LINE 5) FIELD GEOMETRY -- L DBC SOMOD ---


        RUFMOD RUF AN  INFMOD K A B C ---
2,.15,0,1,4.68,.547,0,0
              2  1.500000E-001          .0000000              1       4.6800000
    5.470000E-001          .0000000          .0000000
ENTER (LINE 5) FIELD GEOMETRY -- L DBC SOMOD ---
100,1,1
              100.0000000              1              1
ENTER (LINE 6) AVERAGE BOTTOM SLOPE -- SOAVG ---
.003
  3.000000E-003
ENTER (LINE 7) MANAGEMENT PARAMETERS -- ZREQ Q TCO ---
10,7,15
              10.0000000        7.0000000       15.0000000
ENTER (LINE 9) SOLUTION PARAMETERS -- SOLMOD LINMOD DTMOD ISUPZA ZADMOD ---
3,2,0,0,0
              3              2          0          0          0
ENTER (LINE 10) NUMERICAL SOLUTION PARAMETERS -- N(STD) ---
10,1,10,0,0
              10
ENTER (LINE 11) DIAGNOSTIC PARAMETERS -- IDIAG IDCH ID2 IPRZA FLGPVE ---
0,0,0,0,0
              0              0          0          0       .0000000
ENTER (LINE 12) PLOTTING PARAMETERS -- IPLOTW IPLOTY IPLOTH IPLOTC IPWAIT ---

0,0,0,0,0
************************************** B O R D E R  I R R I G A T I O N  F L O W **************************************

  calibration of model kinematic-wave


                    H Y D R A U L I C  P R O P E R T I E S  O F  C R O P  A N D  S O I L
                        D I M E N S I O N E D                    D I M E N S I O N L E S S

ROUGHNESS ---
MANNING N (COEFFICIENT) = .1500 FT**(1/6)      = .1500 M**(1/6)      EXPONENT = .0000E+00
                                          DIMENSIONLESS DRAG COEFFICIENT    D* = .9999E+00

INTAKE CHARACTERISTICS ---              IN INFILTRATION FORMULA  Z = K*T**A + B*T - C  ---

              K = 1.8425   IN/HR**A      = 4.6800   CM/HR**A
                = .1962E+00 IN/MIN**A    = .4984E+01 MM/MIN**A
                = .1742E-02 FT/SEC**A    = .5308E-03 M/SEC**A
                                                              K* = .1538E+00
              A = .5470              = .5470              A = .5470
              B = .0000 IN/HR        = .0000 CM/HR        B* = .0000E+00
              C = .0000 IN           = .0000 CM           C* = .0000E+00
```
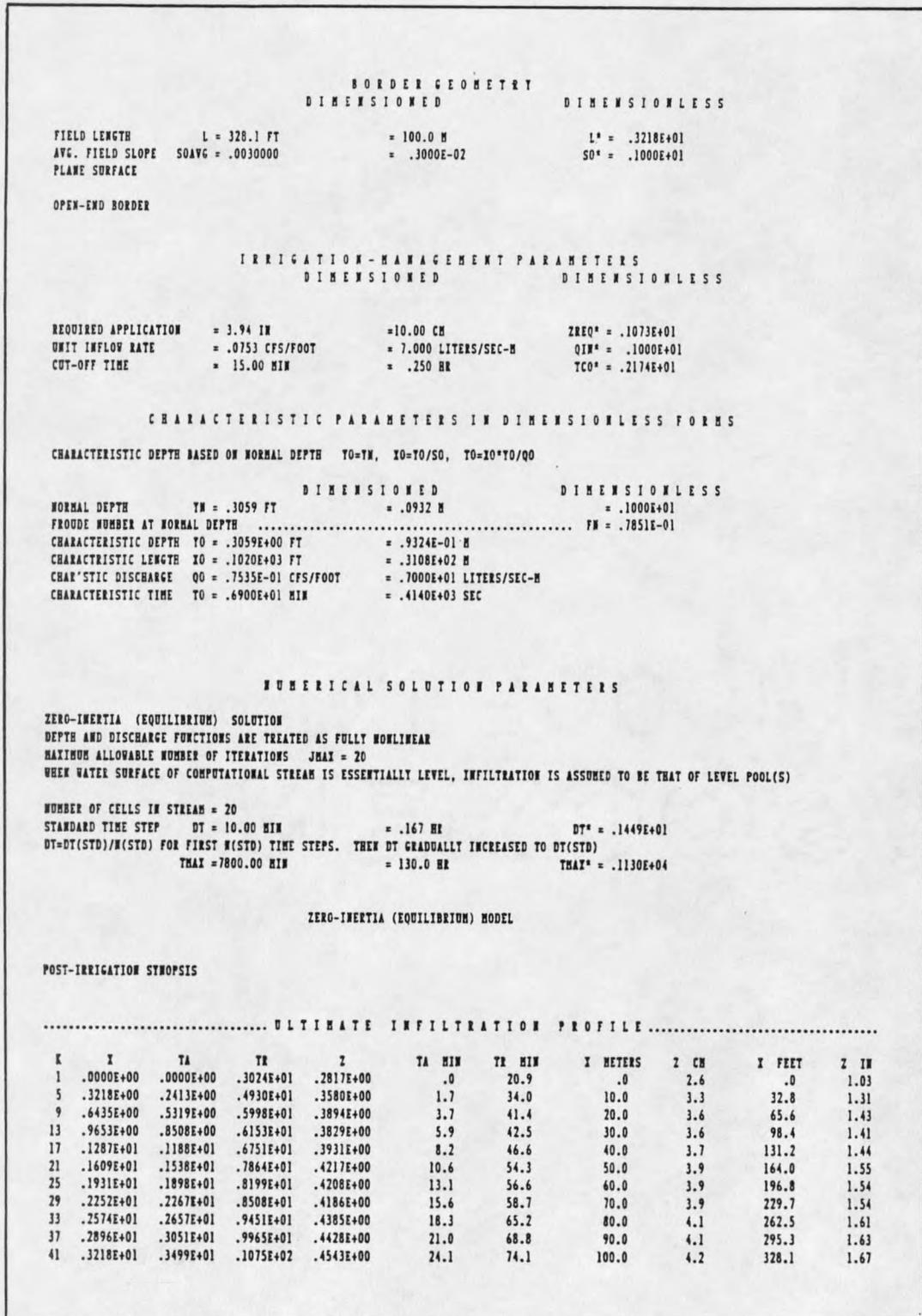
Figure 29. Continued.

```
                                    B O R D E R   G E O M E T R Y
                                    D I M E N S I O N E D              D I M E N S I O N L E S S

          FIELD LENGTH       L = 328.1 FT             = 100.0 M              L* = .3218E+01
          AVG. FIELD SLOPE   SOAVG = .0030000         = .3000E-02            SO* = .1000E+01
          PLANE SURFACE

          OPEN-END BORDER




                              I R R I G A T I O N - M A N A G E M E N T   P A R A M E T E R S
                                    D I M E N S I O N E D              D I M E N S I O N L E S S


          REQUIRED APPLICATION  = 3.94 IN            =10.00 CM              ZREQ* = .1073E+01
          UNIT INFLOW RATE      = .0753 CFS/FOOT     = 7.000 LITERS/SEC-M   QIN*  = .1000E+01
          CUT-OFF TIME          = 15.00 MIN          = .250 HR             TCO*  = .2174E+01


                      C H A R A C T E R I S T I C   P A R A M E T E R S   I N   D I M E N S I O N L E S S   F O R M S

          CHARACTERISTIC DEPTH BASED ON NORMAL DEPTH   YO=YN, XO=YO/SO, TO=XO*YO/QO

                                                   D I M E N S I O N E D          D I M E N S I O N L E S S
          NORMAL DEPTH         YN = .3059 FT            = .0932 M               = .1000E+01
          FROUDE NUMBER AT NORMAL DEPTH  ..................................................... FN = .7851E-01
          CHARACTERISTIC DEPTH   YO = .3059E+00 FT       = .9324E-01 M
          CHARACTRISTIC LENGTH   XO = .1020E+03 FT       = .3108E+02 M
          CHAR'STIC DISCHARGE    QO = .7535E-01 CFS/FOOT = .7000E+01 LITERS/SEC-M
          CHARACTERISTIC TIME    TO = .6900E+01 MIN      = .4140E+03 SEC

                              N U M E R I C A L   S O L U T I O N   P A R A M E T E R S

       NORMAL-DEPTH KINEMATIC-WAVE SOLUTION
       DEPTH AND DISCHARGE FUNCTIONS ARE TREATED AS FULLY NONLINEAR
       MAXIMUM ALLOWABLE NUMBER OF ITERATIONS   JMAX = 20

       NSTD= 10




                                    K I N E M A T I C - W A V E   M O D E L

       IN KINEMATIC-WAVE SOLUTION, CHARACTERISTICS EMANATING FROM X=0 ARE SEPARATED BY DT= .1287E+00 = .8880E+00 MIN

       POST-IRRIGATION SYNOPSIS


       ...................................... U L T I M A T E   I N F I L T R A T I O N   P R O F I L E ...........................................

          K      X         TA         TB         Z        TA MIN    TB MIN    X METERS    Z CM      X FEET    Z IN
          1   .0000E+00  .0000E+00  .2174E+01  .2351E+00     .0      15.0        .0        2.2        .0       .86
          5   .3218E+00  .3304E+00  .3839E+01  .3055E+00    2.3      26.5       10.0        2.8      32.8      1.12
          9   .6435E+00  .6741E+00  .4736E+01  .3310E+00    4.7      32.7       20.0        3.1      65.6      1.21
         13   .9653E+00  .1025E+01  .5486E+01  .3484E+00    7.1      37.8       30.0        3.2      98.4      1.28
         17   .1287E+01  .1383E+01  .6144E+01  .3610E+00    9.5      42.4       40.0        3.4     131.2      1.33
         21   .1609E+01  .1748E+01  .6723E+01  .3698E+00   12.1      46.4       50.0        3.4     164.0      1.36
         25   .1931E+01  .2117E+01  .7276E+01  .3772E+00   14.6      50.2       60.0        3.5     196.8      1.38
         29   .2252E+01  .2493E+01  .7770E+01  .3819E+00   17.2      53.6       70.0        3.6     229.7      1.40
         33   .2574E+01  .2874E+01  .8249E+01  .3858E+00   19.8      56.9       80.0        3.6     262.5      1.42
         37   .2896E+01  .3259E+01  .8678E+01  .3875E+00   22.5      59.9       90.0        3.6     295.3      1.42
         41   .3218E+01  .3650E+01  .9108E+01  .3890E+00   25.2      62.8      100.0        3.6     328.1      1.43


       .......................................... M E A S U R E S   O F   M E R I T   O F   C O M P U T A T I O N ...........................................

       COMPUTATIONAL VOLUME BALANCE    VQ= .2174E+01    VZ= .1149E+01    VRO= .1034E+01   .......... RELATIVE VOLUME ERROR =-.4054E-02
```

Figure 29. Continued.

```
......................... S Y N O P S I S   O F   R E S U L T S   O F   I R R I G A T I O N .........................

                                                                    HOURS    MINUTES   DIMENSIONLESS
T CO      (TIME OF CUT OFF) ..............................................    .25     15.00     .2174E+01
T L       (DURATION OF ADVANCE) ..........................................    .42     25.18     .3650E+01
T R       (TIME RECESSION STARTS AT UPSTREAM END) ........................    .25     15.00     .2174E+01
T FR      (TIME RECESSION STARTS AT DOWNSTREAM END) ......................   1.05     62.84     .9108E+01
T E       (TIME ALL SURFACE WATER DISAPPEARS) ............................   1.05     62.84     .9108E+01

                                                                    ENGLISH  METRIC    DIMENSIONLESS
                                                                    FT**3/FT M**3/M
V Q       (APPLIED VOLUME) ...............................................  67.811    6.300     .2174E+01
V Z       (INFILTRATED VOLUME) ...........................................  35.848    3.330     .1149E+01
V RO      (RUNOFF VOLUME) ................................................  32.238    2.995     .1034E+01
                                                                                                          % OF
                                                                    ENGLISH  METRIC   DIMENSIONLESS    APPLIED
                                                                                                         DEPTH

Y MAX U   (MAXIMUM DEPTH OF SURFACE STREAM ATTAINED AT UPPER END) .........    .31 FOOT  9.32 CM   .1000E+01



Y MAX D   (MAXIMUM DEPTH OF SURFACE STREAM ATTAINED AT LOWER END) .........    .28 FOOT  8.62 CM   .9248E+00
Y MAX     (MAXIMUM DEPTH OF SURFACE STREAM ATTAINED AT ANY POINT) .........    .31 FOOT  9.32 CM   .1000E+01
X YMAX    (LOCATION OF POINT OF MAXIMUM DEPTH) ............................    .00 FOOT   .00 M    .0000E+00

Z MIN     (MINIMUM DEPTH OF INFILTRATION) ................................    .86 INCH  2.19 CM   .2351E+00      34.8 %
Z MAX     (MAXIMUM DEPTH OF INFILTRATION) ................................   1.43 INCH  3.63 CM   .3890E+00      57.6 %
Z LQ      (AVERAGE LOW-QUARTER DEPTH OF INFILTRATION) ....................   1.13 INCH  2.86 CM   .3067E+00      45.4 %
Z REQ     (REQUIRED DEPTH OF INFILTRATION) ...............................   3.94 INCH 10.00 CM   .1073E+01     158.7 %

Z Q       (AVERAGE APPLIED DEPTH      VQ/L) ..............................   2.48 INCH  6.30 CM   .6757E+00     100.0 %
Z AVG     (AVERAGE INFILTRATED DEPTH  VZ/L) ..............................   1.31 INCH  3.33 CM   .3572E+00      52.9 %
Z RO      (AVERAGE DEPTH OF RUNOFF    VRO/L) .............................   1.18 INCH  3.00 CM   .3212E+00      47.5 %

Z DP ZREQ (AVERAGE DEPTH OF DEEP-PERCOLATION VOLUME BASED ON GIVEN REQUIRED DEPTH)  .00 INCH   .00 CM   .0000E+00    .0 %
Z DP ZMIN (AVERAGE DEPTH OF DEEP-PERCOLATION VOLUME BASED ON ZREQ = ZMIN)  .45 INCH  1.14 CM   .1221E+00      18.1 %
Z DP ZLQ  (AVERAGE DEPTH OF DEEP-PERCOLATION VOLUME BASED ON ZREQ = ZLQ)   .20 INCH   .50 CM   .5316E-01       7.9 %
Z U ZREQ  (AVERAGE OF INFILTRATED DEPTHS LESS THAN OR EQUAL TO REQUIRED DEPTH) 1.31 INCH  3.33 CM   .3572E+00    52.9 %
Z U ZMIN  (AVERAGE OF INFILTRATED DEPTHS LESS THAN OR EQUAL TO ZMIN)       .86 INCH  2.19 CM   .2351E+00      34.8 %
Z U ZLQ   (AVERAGE OF INFILTRATED DEPTHS LESS THAN OR EQUAL TO ZLQ)       1.12 INCH  2.83 CM   .3040E+00      45.0 %

UC C      (CHRISTIANSEN UNIFORMITY COEFFICIENT) ................................................   .924
UC H      (HSPA UNIFORMITY COEFFICIENT) .......................................................   .923
DU        (DISTRIBUTION UNIFORMITY          ZMIN/ZAVG) .........................................   .658
DU LQ     (LOW-QUARTER DISTRIBUTION UNIFORMITY   ZLQ/ZAVG) .....................................   .859
RP        (RUNOFF FRACTION IN PERCENT        VRO/VQ ) ..........................................   47.54%
                                                                         BASED ON   BASED ON    BASED ON
                                                                         GIVEN ZREQ  ZREQ=ZMIN  ZREQ=ZLQ
IE        (IRRIGATION EFFICIENCY           ZU/ZQ ) ....................   52.86%      34.80%      45.00%
UZ        (USEFUL FRACTION OF INFILTRATED VOLUME  ZU/ZAVG) ...........   1.000        .658        .851
SE        (STORAGE EFFICIENCY              ZU/ZREQ) ..................   33.30%      100.00%      99.12%
AAP       (PERCENT OF TOTAL AREA ADEQUATELY IRRIGATED) ...............    .00%       100.00%      89.58%
DR        (DEFICIENCY RATIO, AVERAGE DEFICIT IN UNDERIRRIGATED AREA, PERCENT OF ZREQ) 66.70%                   8.41%
```

Figure 29. Continued

APPENDIX C

Field Data Prepared by Merriam et al. (1978)

Table 12. Physical characteristics for border irrigation.

Variables	Description
Crop	Alfalfa
Root Zone Depth	183 cm
Soil	Sandy Loam
Required Application	7.4 cm
Border Width	6.4 m
Border Length	259 m
Slope	0.5%
Flow	34 l/s

Table 13. Advance and recession data.

Station	Advance Time (min.)			Recession Time (min.)		
(meters)	Watch	Diff.	Cum.	Watch	Diff.	Cum.
0+00	10:51			12:27	8	96
0+30	10:59	8	8	12:59	32	128
0+60	11:12	13	21	13:18	19	147
0+90	11:26	14	35	13:29	11	158
1+22	11:41	15	50	13:33	4	162
1+52	11:59	18	68	13:38	5	167
1+83	12:18	19	87	13:41	3	170
2+13	12:40	22	109	13:45	4	174
2+44	13:06	26	135	13:43	-2	172
2+59	13:32	26	161	13:42	-1	171

Cutoff Time= 88 min.

Table 14. Adjusted infiltration information.

Time (min.)	Accumulated Infiltration Depth (cm)
4	1.3
10	2.4
30	4.5
60	6.1
100	10.4
200	16.5

Table 15. Depth infiltrated.

Station (meters)	Depth (cm)
0+00	9.6
0+30	11.0
0+60	11.5
0+90	11.5
1+22	10.8
1+52	10.0
1+83	9.1
2+13	7.6
2+44	5.9
2+59	2.2

APPENDIX D

The Computation of Soil Infiltration Characteristics

In order to compute the soil infiltration characteristics, a mathematical procedure developed by Davis (1943) was followed to solve for the constants K, A, and C in equation (2.1; Chapter 2). The equation (2.1) can be rewritten in logarithmic form as follows.

$$Log(z - C) = LogK + A\ Logt \qquad (D.1)$$

To solve the equation (D.1), two points must have been selected from Table 14 (Appendix C). Davis (1943) suggested the highest and the lowest point to be selected so that:

$$For \quad t_1 = 4\ min, \quad z_1 = 1.3\ cm$$
$$For \quad t_2 = 200\ min. \quad z_2 = 16.5\ cm$$

Equation (D.2) then was used to solve for t_3,

$$t_3 = (t_1.t_2)^{0.5} \qquad (D.2)$$

$$t_3 = (4X200)^{0.5}$$

$$t_3 = 28\ min.$$

Table 14 (Appendix C) was utilized to interpolate a value of 4.4 cm for z_3 corresponds to t_3 equal to 28 minutes. The constant C then was computed using the equation (D.3):

$$C = \frac{z_1.z_2 - (z_3)^2}{z_1 + z_2 - 2z_3} \qquad (D.3)$$

$$C = \frac{[(1.3)(16.5) - (4.4)^2]}{[1.3 + 16.5 - 2(4.4)]} = 0.2322$$

Substituting the C and the data presented in Table 14 (Appendix C) into equation (D.1) yields the following six equations:

$$0.0285 = LogK + 0.6021A$$
$$0.3360 = LogK + 1.0000A$$
$$0.6302 = LogK + 1.4771A$$

$$0.7685 = LogK + 1.7782A$$
$$1.0072 = LogK + 2.0000A$$
$$1.2113 = LogK + 2.3010A$$

Adding the first three and the last three eqations,

$$0.9947 = 3LogK + 3.0792 \qquad (D.4)$$

$$2.9870 = 3LogK + 6.0792 \qquad (D.5)$$

Dividing equations (D.4) and (D.5) by 3,

$$0.3316 = LogK + 1.0264A \qquad (D.6)$$

$$0.9957 = LogK + 2.0264A \qquad (D.7)$$

Substituting equation (D.7) from equation (D.6) yields,

$$A = 0.6641$$

Substituting for A in equation (D.6) and solving for K,

$$0.3316 = LogK + (1.0264)(0.6641)$$
$$K = 0.4467$$