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

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.

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A thesis submitted in partial fulfillment
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of

Master of Science

in

Agricultural Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

June 1987

APPROVAL

of a thesis submitted by

Toraj Ghofrani

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style and consistency, and is ready for submission to the College of Graduate Studies.

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21 May 87 — Date

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ACKNOWLEDGMENTS

I would like to gratefully acknowledge the assistance and guidance provided by my thesis committee composed of Dr. G.L. Westesen, chairman, Dr. W.E. Larsen, and Dr. R.L. Brustkern. In memory of my father (Mohammad Ghofrani), I would like to express my gratitude for his devoted efforts which made this work possible. Finally, I would like to recognize the youth of my country who have lost their lives in an unwanted war.

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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.

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/TxL 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).

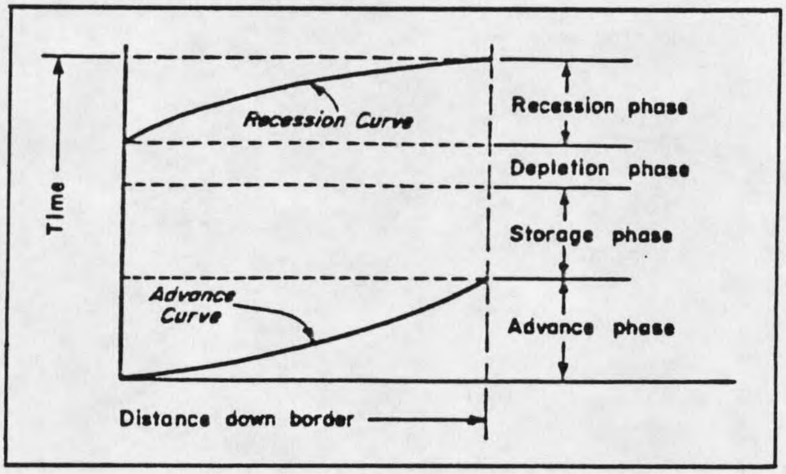

Figure 1. Schematic description of border irrigation phases.

<u>Advance Phase</u>

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.

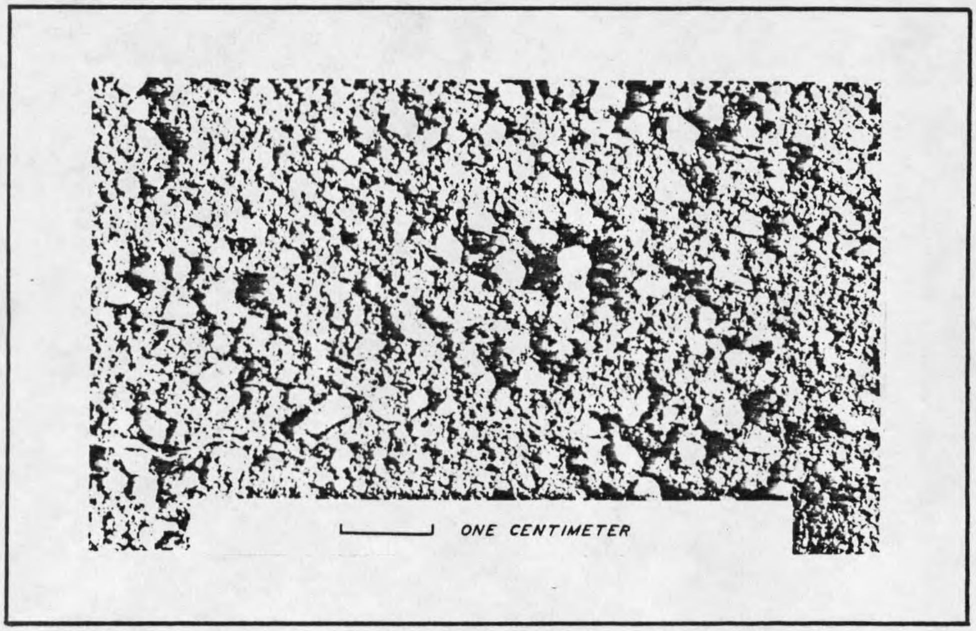

Figure 2. Soil surface before rainfall (Duley et al., 1939)