Implementation and evaluation of surge flow border irrigation
by Samir Mohamed Ismail

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering
Montana State University

Abstract:
Surge flow border irrigation can be accomplished by accumulating, then releasing water and letting it flow down the field. To apply this concept to border irrigation a dosing siphon and automatic drop gate were designed and tested. The dosing siphon holds back the water because of trapped air, and has a maximum practical flow of 22 L/s. The drop gate can be built for virtually any head and flow rate. The gate opens automatically when the water level on the upstream side of the gate rises to a predetermined level and remains open until the water surface drops to a lower predetermined level. The gate then returns automatically to its closed position by action of a counter balance weight. The automatic drop gate was tested in the laboratory and a discharge equation developed.

A mathematical model based on the differential storage equation was developed to simulate field conditions. The model was verified with laboratory tests. Field experiments were also conducted to evaluate surge flow border irrigation systems using the automatic drop gate. Surge flow and conventional continuous flow were compared. The surge flow treatments showed a higher uniformity of water penetration. Surge flow also showed a higher potential application efficiency than continuous irrigation under the same inflow. The higher efficiency of surge flow can be attributed to the rapid advance of the water front which is due to the accumulation of the small inflow, reduction in infiltration, and reduction in surface hydraulic roughness. Both the dosing siphon and automatic drop gate have practical application under appropriate field conditions.

APPROVAL

of a thesis submitted by

Samir Mohamed Ismail

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

Feb. 2, 1984 — Date

Gerald Westesen — Chairperson, Graduate Committee

Approved for the Major Department

Feb. 2, 1984 — Date

Fred F. Willson — Head, Major Department

Approved for the College of Graduate Studies

Feb. 3, 1984 — Date

Henry L. Parsons — Graduate Dean

IMPLEMENTATION AND EVALUATION OF SURGE FLOW BORDER IRRIGATION

by

Samir Mohamed Ismail

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Doctor of Philosophy

in

Civil Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

March 1984

STATEMENT OF PERMISSION TO USE

ACKNOWLEDGMENTS

The author would like to thank the Agricultural Engineering Department and the Montana Agricultural Experiment Station for their financial support of this project.

The writer is greatly indebted to Dr. G. L. Westesen, for his supervision, valuable guidance, suggestions, and assistance in revising the manuscript. Particular appreciation is extended to Dr. W. E. Larsen for his sincere advice and valuable guidance in the development of automatic equipment for surge flow. Thanks to Drs. T. L. Hanson and R. L. Brustkern for their assistance and scientific advice. A special thanks to Professor T. T. Williams who helped to set up a joint program between the Civil Engineering Department and the Agricultural Engineering Department for this Ph. D. program.

The author wishes to express his appreciation and thanks to the secretary of the Agricultural Engineering Department, Darlene Ritchey, for her valuable guidance on the use of word processor during preparation of this dissertation.

Finally, the author's gratitude is to his wife, Mervat, for her help, patience, and encouragement.

TABLE OF CONTENTS

TABLE OF CONTENTS—Continued

TABLE OF CONTENTS--Continued

LIST OF TABLES

LIST OF TABLES--Continued

LIST OF FIGURES

LIST OF FIGURES--Continued

LIST OF FIGURES—Continued

ABSTRACT

Surge flow border irrigation can be accomplished by accumulating, then releasing water and letting it flow down the field. To apply this concept to border irrigation a dosing siphon and automatic drop gate were designed and tested. The dosing siphon holds back the water because of trapped air, and has a maximum practical flow of 22 L/s. The drop gate can be built for virtually any head and flow rate. The gate opens automatically when the water level on the upstream side of the gate rises to a predetermined level and remains open until the water surface drops to a lower predetermined level. The gate then returns automatically to its closed position by action of a counter balance weight. The automatic drop gate was tested in the laboratory and a discharge equation developed.

A mathematical model based on the differential storage equation was developed to simulate field conditions. The model was verified with laboratory tests. Field experiments were also conducted to evaluate surge flow border irrigation systems using the automatic drop gate. Surge flow and conventional continuous flow were compared. The surge flow treatments showed a higher uniformity of water penetration. Surge flow also showed a higher potential application efficiency than continuous irrigation under the same inflow. The higher efficiency of surge flow can be attributed to the rapid advance of the water front which is due to the accumulation of the small inflow, reduction in infiltration, and reduction in surface hydraulic roughness. Both the dosing siphon and automatic drop gate have practical application under appropriate field conditions.

CHAPTER 1

INTRODUCTION

Field irrigation is concerned with transference of water from a conveyance system to the plant root zone. The logical possibilities for irrigation are:

(a) to run the water over the surface so that it infiltrates the soil;

(b) to pass water into the soil at depth so capillary action raises it to the root zone, or;

(c) to cause water to fall to the ground in such a way that neither crop nor soil is damaged.

These are the basic categories of water application practice known as surface irrigation, sub-irrigation, and overhead irrigation. Each has inherent advantages and hazards which affect its value for a particular situation. The demands on water supplies are steadily increasing and in many areas the ground water supplies are being depleted. Irrigation is the largest consumer of water in many parts of the world and, hence, has received a great deal of attention during the past decade and will be receiving greater attention in the future.

In some areas surface irrigation has earned a reputation for being inefficient and wasteful. About two-thirds of the 25 million hectares (61 million acres) of irrigated land in the U.S. is now served by surface means (Irrigation Journal, 1979). The percentage is even higher in many other parts of the world. Anticipated shortages of water and the high cost of energy to drive alternative systems, such as sprinklers, suggest that surface irrigation will remain popular, especially if abuses can be avoided. High runoff and deep percolation losses are cited as prime problems. However, there is nothing inherent about surface irrigation that causes inefficiencies. These inefficiencies are commonly the result of improper management and the irrigator's inability to completely control the water because of inadequate equipment.

Surface irrigation uses open channel flow to spread water over a field. The driving force in such systems is gravity, so surface irrigation is also called gravity flooding. Surface irrigation systems generally require a smaller investment than do other types of irrigation systems. However, this is not always the case, especially if extensive land forming is needed for an efficient system. In fact, the need for extensive land forming for surface irrigation is one of the main reasons other types of irrigation systems have been developed. In addition, some soils that are shallow, erosive, or on steep slope simply cannot be surface irrigated.

Surface irrigation can be accomplished by several application methods. These include border, furrow, check, and basin. In each case water moves over the land surface in an open channel flow. The water may be contained in small earth channels called furrows or corrugations or it may move as shallow overland flow over a carefully smoothed soil surface as in border irrigation. Aside from differences in channel geometry and boundary conditions, the basic flow characteristics are much the same in all of the surface methods.

In border irrigation, water moves over the soil surface as shallow overland flow. The soil surface is permeable to water. The length of the border strip parallel to the flow is usually great with respect to the width. The surface may have a zero to small slope longitudinally and is preferably level in the transverse direction. Surface water depth is usually very small with respect to border width. The land surface may or may not be vegetated.

In the operation of border irrigation systems a relatively large stream of water is turned into the strip at the upper end. The water ponds at the upper end to an appreciable depth and also moves down the strip as a wave. The stream is generally turned off before it reaches the lower end which is then irrigated by water which flows down from the upper portion. In order to adequately irrigate the lower portion some runoff or ponding is usually required. The border strip method of irrigation is complicated. However, when adequately designed and properly used it is probably the most efficient and requires the least labor of all methods.

In the basin method the field to be irrigated is divided into level areas bounded by dikes or ridges. Water is turned in at one or more points until the desired gross volume has been applied to the area. The flow rate must be large enough to cover the entire basin in approximately 75 percent of the time required for the soil to absorb the desired amount of water. Water is ponded until it infiltrates. This irrigation method is best suited to soils of moderate to low intake rates. Basin irrigation can also be applied to soils that have a moderately high to high intake rate but basin areas need to be small.

In some situations the farmer receives a small stream of water under a continuous delivery system. This continuous delivery system is often inefficient and excessive water use contributes to drainage problems. Attention has therefore been given to the advance phase of surface irrigation, which is primarily controlled by stream size, because of its bearing on intake opportunity time. Surface irrigation design and management objectives are generally to complete the advance phase of the irrigation as quickly as possible so that differences in intake opportunity time are minimized. Large stream sizes are required for the water to advance quickly. Cutback streams or runoff recovery systems can be used to minimize the runoff and deep percolation losses during the intake phase.

Automatic surface irrigation systems reduce labor, energy, and water inputs and maintain or increase farm irrigation efficiency. Automation is the use of mechanically or electrically actuated gates, structures, controllers, and other devices and systems to automatically control the amount of water diverted and applied.

The ideal irrigation system would have a low energy requirement, be automated, provide nearly instantaneous advance, and prevent runoff during the intake phase.

Stringham and Keller (1979) suggested surge flow as a method of automating cutback furrow irrigation. Surge flow is in essence an operational practice in which irrigation is accomplished by cycling inflow to the field to produce a series of short pulses of water flowing over the field surface. These pulses are termed hydraulic surges, and thus lead to the name surge flow. The pulses are independent water applications whose sum is designed to satisfy the antecedent soil moisture deficit. These intermittent water applications lead to a discontinuity in the infiltration process, the result of which is often a reduction in surface layer permeability. However, this effect is widely variable depending on soil compaction and prior wetting history, surface water velocities, and duration of on-off periods. The exact mechanisms of surge flow irrigation are not completely known. However, the surge flow irrigation should in general yield the following results:

1. The alternating on-off system of controlling water delivery should achieve nearly uniform water penetration over the entire field.
2. Surges should provide water application efficiencies comparable to sprinkling without the high energy costs required to operate the sprinklers.
3. Surge systems should be partially or fully automated to reduce labor requirements and enable irrigation timing to best suit the crop and soil conditions.

The objectives of this study are:

1. To develop automated equipment for the practical application of surge irrigation to borders and basins. The automated equipment should be capable of collecting small inflows for a

period of time in a head ditch or a reservoir and discharging the water when the water surface rises to a certain level.

2. To develop a mathematical model which embodies the characteristics of the head ditch, the automatic device and required flow rates and which will yield the cycle time required for surge flow border irrigation.

3. To conduct field evaluations of surge flow border irrigation devices and systems and compare the surge flow systems with conventional continuous flow systems.

CHAPTER 2

SURFACE IRRIGATION THEORY

General

The border-strip method of surface irrigation utilizes a strip of land sloping longitudinally and level or nearly so laterally across the strip. The water is bounded by borders (ridges) to restrain the lateral flow of the water. In operation, a stream of water is turned into the strip at the upper end. It ponds there to an appreciable depth and also moves down the strip as a wave. The stream is turned off before the wave reaches the lower end which is then irrigated by water which was ponded on the upper portion.

Phases of a typical irrigation are shown in Fig. 1 and described in the following manner.

Advance Phase

The rate of advance down a border will be affected by five major factors. The first is the unit inflow. This may vary throughout the irrigation or remain constant.

The slope of the border determines the rate at which energy is added to the flowing water. Only a single average slope of the entire irrigation run is normally considered.

The forces restraining flow are those due to resistance—both from the soil surface and vegetation. The soil surface changes during an irrigation and between irrigations. The vegetative roughness is a function of the vegetation involved. Vegetation factors considered are stem rigidity, stem length, stem diameter and stem density, and the presence of leaves. These factors must be considered in combination and make the roughness representation difficult. Nevertheless, most analyses to date consider only a single roughness parameter, such as Manning's n.

Another factor affecting advance rate is the infiltration characteristic of the soil. Infiltration varies with time (during and between irrigations) and space (location within the field). Again, approximations are necessary. It is common in the field of irrigation to use a two-parameter infiltration representation. The most popular are the Kostiakov-Lewis (original or modified), the Philip, or the Soil Conservation Service representations.

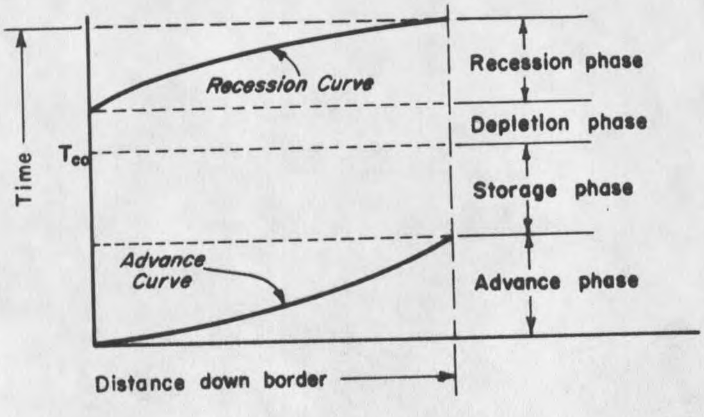

Figure 1. Definition sketch showing certain border irrigation terms.

Channel shape is the final variable affecting advance. Borders are considered a wide shallow rectangular channels. Therefore, the hydraulic radius is considered equal to the depth of flow.

Storage Phase

When water first reaches any point on the soil surface, the infiltration is generally high. The infiltration rate rapidly declines, however, often to some relatively constant value. Thus, when the water reaches the end of the border, the infiltration rate is constant or decreasing at every point within the border. The tail end of the border may have a dam over which the water cannot pass, and thus water begins to accumulate on the soil, as well as within the profile. Even if no dam exists, the soil is absorbing water. This phase, during which water covers the entire soil surface, is known as the storage phase. The storage phase ends when the inflow ceases (time T_{co}).

Depletion Phase

At some appreciable time after turning the water off the ponded water at the upper end will disappear by infiltration and movement on down the strip. This interval of time between turn off and disappearance is known as the depletion phase or as the recession lag time.

Recession Phase

The water that once covered the surface has either entered the soil or flowed to a lower portion of the field. This is known as the recession phase. Ideally this recession of water from the surface begins at the head end and progress down the field until the water has either entered the soil or runoff. When the ponded water has been absorbed by the soil (or runoff at the end), the irrigation is complete.

Infiltration

Infiltration is the term applied to the process of water entry into the soil, generally by downward flow through all or part of the soil surface. The rate of this process determines how much water will enter the root zone, and how much if any, will runoff.

The infiltration rate is defined as the volume flux of water flowing into the profile per unit of soil surface area. This flux, with units of velocity, has also been referred to as infiltration velocity. For the condition wherein the water supply exceeds the ability of the soil to absorb water, infiltration proceeds at a maximal rate, which Horton (1940) called the soil's infiltration capacity. The infiltration rate generally decreases with time. Thus, the cumulative infiltration, which is the time integral of the infiltration rate, has a curvilinear time dependence with a gradually decreasing slope. As time elapses the infiltration rate asymptotically approaches a constant rate. This rate is termed the final infiltration capacity, or basic intake rate.

The time of irrigation is fixed by the quantity of water required to replenish the soil-moisture supply and the rate of infiltration. The length of time during which water is held on the soil surface also helps determine the length of run for border-strips or irrigation furrows and the size of the irrigation stream.

<u>Infiltration Equations</u>

The historical order of appearance of some widely applied infiltration rate equations are presented as follows.

The earliest equation was introduced by Green and Ampt (1911),

$$f = f_c + (b/F) \tag{2.1}$$

where

f = infiltration rate

f_c = final constant infiltration rate

F = cumulative infiltration

b = characterizing constant

The next equation is that of Kostiakov (1932),

$$f = K_k\ t^{-\alpha} \tag{2.2}$$

where

t = time after infiltration starts

K_k, α = constants which depend on the soil and initial conditions.

The parameters in these equations have no physical interpretation and must be evaluated from experimenal data.

In some irrigation studies an extended or modified Kostiakov equation is used as follows,

$$F = a\ t^b + c\ t \tag{2.3}$$

where a, b, and c are constants which must be determined experimentally.

The third equation was derived by Horton (1940),

$$f = f_c + (f_o - f_c)\ e^{-\beta t} \tag{2.4}$$

where

f_o = infiltration capacity at t = 0

β = a soil parameter which controls the rate of decrease of infiltration rate.

The equation contains three constants which must be evaluated experimentally.

The fourth equation is that of Philip (1957),

$$f = f_c + (1/2)\ s\ t^{-1/2} \tag{2.5}$$

where s is a parameter which Philip called sorptivity. Sorptivity has a physical meaning involving the geometry of the soil pore spaces, the surface tension and the viscosity of water.

The fifth equation was proposed by Holtan (1961):

$$f = f_c + a\ (S_t - F)^n \tag{2.6}$$

where

S_t = water storage capacity of the soil's first impeding strata

a, n = constants dependent on soil type, surface and cropping conditions.

The USDA, Soil Conservation Service (1974), classified soils into intake families. The equation of these families takes the following form,

$$F = a\ t^b + c \qquad (2.7)$$

where

a, b, c = constants unique to each intake family

Border Irrigation Hydraulics

The phenomenon of surface irrigation is characterized by unsteady varied flow and is further complicated by the fact that boundaries are moving and that interfacial tension forces are in effect. As a natural phenomenon, the laws of mass, energy, and momentum conservation must be satisfied. It is known that surface water flow in irrigation can be described by the equations of Saint-Venant (Fig. 2). The following are the governing flow equations.

Saint-Venant Equations

The partial differential equations of Saint-Venant (Chow, 1959; Henderson, 1966; Strelkoff, 1969), governing the unsteady, nonuniform surface water flow in border irrigation consist of an equation of continuity comprising a volume balance and an equation of motion, representing an impulse-momentum balance. For surface irrigation hydraulics it can be assumed that the flow is essentially one dimensional, i.e, that it is effectively guided by the channel walls. The channel is assumed to be prismatic and it is also assumed that the flow is gradually varied, i.e, that the pressure distribution in all cross sections is hydrostatic. An additional assumption is that the velocity distribution in each cross section is virtually uniform, but drops to zero at the walls. A further assumption is that the resistance to the flow introduced by soil surface roughness and plant stems and leaves, is dependent upon flow depth and velocity in the same way as if the flow were steady and uniform and without seepage. Finally, the bottom slope is assumed small so that the cosine of its angle with the horizontal is essentially unity. The effect of these assumptions was discussed at length by Strelkoff (1969).

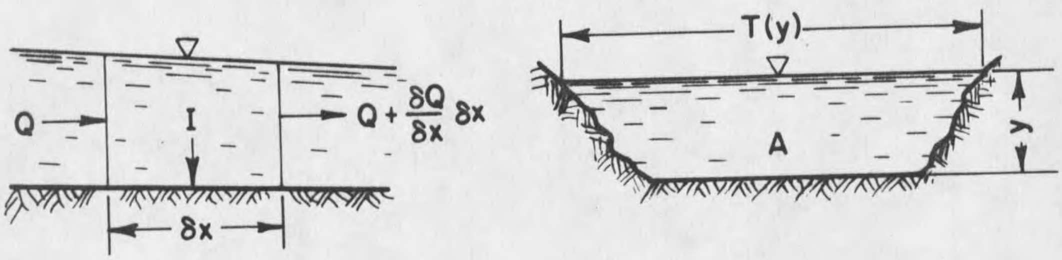

Figure 2. Definition sketch for Saint-Venant Eguations.

The continuity equation (Fig. 2) is

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial X} + I = 0 \tag{2.8}$$

where

A = cross-sectional flow area taken at the middle of the element.

Q = discharge

I = volumetric rate of infiltration per unit length of channel

An impulse-momentum balance states that the sum of the net hydrostatic pressure force on the water instantaneously contained within a slice, plus the gravitational force, minus the resisting force of wall friction and plant retardance; equals the momentum net flux out of the slice, plus the rate at which momentum builds within the slice. Stated mathematically, in the above order, this is

$$- \gamma A \frac{\partial y}{\partial X} \partial X + \gamma A S_o \partial X - F \partial X = \partial X \frac{\partial(\rho Q V)}{\partial X} + \frac{\partial(\rho V A \partial X)}{\partial t}$$

In the above equation, γ is the unit weight of water, y(X,t) is the depth of flow, S_o is the bottom slope , F is the total resisting force per unit length of channel, V(X,t) = Q(X,t)/A(y) is the average velocity of flow and ρ is the mass density of water. Considering zero-velocity components for the flow that is drawn off in soil infiltration, there is no loss of momentum by the water within the slice from this source. Division of the equation by the weight of the slice and passage to the limit $\partial X \longrightarrow 0$ yields the equation of motion

$$\frac{1}{g} \frac{\partial V}{\partial t} + \frac{V}{g} \frac{\partial V}{\partial X} + \frac{\partial y}{\partial X} = S_o - S_f + \frac{IV}{Ag} \qquad (2.9)$$

The complete solution of Eqs.(2.9) and (2.8) either by finite difference techniques or the method of characteristics is commonly known as a full hydrodynamic model (Bassett and Fitzsimmons, 1976; Katapodes and Strelkoff, 1977).

Kinematic-Wave Equations

The kinematic-wave approximation can be obtained by setting the right-hand side only of Eq. (2.9) equal to zero. The method fails for any stage of an irrigation where the bottom slope approaches the horizontal anywhere in the flow. In a kinematic wave the surface flow at all points is considered to be at normal depth. The application of kinematic-wave theory to border-irrigation flow was studied by Smith (1972).

Zero-Inertia Equations

In the case of border irrigation, the depths and velocities are typically so small as to suggest that the acceleration or inertial terms which are the first two terms of Eq. (2.9) are small compared to the remaining terms and could be safely neglected. The first operational zero-inertia model of the complete irrigation process reported by Strelkoff and Katapodes (1977) neglected these terms.

Along with Eq. (2.8) the governing equation becomes,

$$\frac{\partial y}{\partial X} = S_o - S_f \qquad (2.10)$$

Volume-Balance Equations

Equation (2.9) can be entirely supplanted by two assumptions regarding the flow of water on the soil surface. The first assumption is that the depth of flow at the upstream end of the field equals normal depth for the given inflow. The second is that the average depth of surface flow is a given constant fraction, r_y, of the normal depth typically $0.7 < r_y < 1.0$. Computations for the advance phase of an irrigation (prior to cutting off the water), based on this volume-balance approach have been executed numerically (Hall, 1956). The solution of the volume balance equation has been expressed in series form by Philip and Farrell (1964) for infiltration equations of the

Kostaikov type or Philip type. Michael (1968) added a solution for an infiltration equation of the Soil Conservation Service type.

At any given time after the start of an irrigation, the stream has advanced to some point X in the field and surface and sub-surface profiles appear as in Fig. 3.

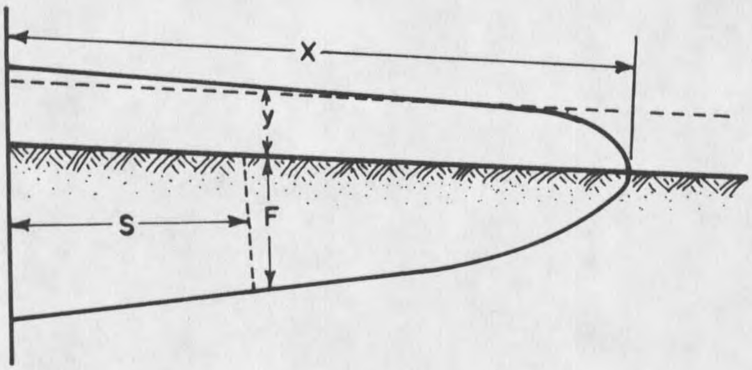

Figure 3. Schematic diagram illustrating the infiltration-advance problem.

The infiltration rate I, is related to the depth of infiltration F, by the formula,

$$I = T \frac{\partial F(X,t)}{\partial t}$$

in which T is the top width of the flow. The depth of infiltration is dependent primarily upon the infiltration opportunity time, i.e, the time the water has been in contact with the soil.

In order to prove that the working equation of Lewis and Milne (1938) can be derived from the general continuity equation the following analysis is proposed.

Integrating Eq. (2.8) with respect to X from 0 to X yields the result

$$Q = \frac{d}{dt} \int_0^X A \, dX + T \frac{d}{dt} \int_o^X F \, dX$$

Integrating this equation with respect to time and dividing the equation by T or the width of border, yields

$$\int_0^t q \, dt = \int_0^X (A/T) \, dX + \int_0^X F \, dX$$

where q is the flow per unit width of border.

If y is defined as the average depth of water on the soil surface, then the cross sectional area of the flow along the soil surface is y X where:

$$y X = \int_0^X (A/T) \, dX$$

where, F is a function of $(t - t_s)$, and X is a function of t_s. The following can be written:

$$F \, dX = F \, (dX/dt_s) \, dt_s$$

$$\int_0^X F \, dX = \int_0^t F_{(t-ts)} \; X'(ts) \; dt_s$$

$$q \, t = y X + \int_0^t F_{(t-ts)} \; X'(ts) \; dt_s \qquad (2.11)$$

where

t_s = value of t at which X(t) = s

$F_{(t-ts)}$ = accumulated infiltration at the point X = s at time t_s

s = value of X at t = t_s, and

$X'_{(ts)}$ = value of dX/dt at t = t_s

Equation (2.11) was originally proposed by Lewis and Milne (1938). Philip and Farrel (1964) analysed the physical restrictions on X and F in Eq. (2.11). The equation is valid if X is a monotonic increasing function of t. This condition on X(t) places a restriction on the form of F(t) for which the analysis is valid. Sufficient conditions are

$$F > 0 \quad , \frac{dF}{dt} > 0 \quad \text{and} \quad \frac{d^2F}{dt^2} < 0$$

Generally, the physical restrictions on F are such that these conditions are realized and Eq. (2.11) is valid. Philip and Farrel (1964), using the Faltung or convolution theorem of Laplace transformation, obtained the general solution of Eq. (2.11) as follows.

$$\frac{X}{q} = L^{-1} \frac{1}{s^3 \; L\{F\} + y \; s^2} \tag{2.12}$$

Equation (2.12) represents the general solution of Eq. (2.11) in terms of Laplace transformation. It can be applied to different forms of F(t), depending on whether the appropriate transformations and inverse transforms can be evaluated readily.

Michael (1968) obtained the following particular solutions of the Soil Conservation Service infiltration equation (Eq. (2.7)):

For a small value of t, i.e, $\frac{Bt^b}{\Gamma(2+b)} < 1$

$$X = \frac{q\ t}{c+y}\left[\frac{1}{\Gamma(2)} - \frac{Bt^b}{\Gamma(2+b)} + \frac{B^2\ t^{2b}}{\Gamma(2+2b)} - \frac{B^3\ t^{3b}}{\Gamma(2+3b)} + \frac{B^4\ t^{4b}}{\Gamma(2+4b)} - \ldots\ldots\right] \tag{2.13}$$

where, $B = \frac{a\ \Gamma(b+1)}{c+y}$

For large value of t, i.e, $\frac{B\ t^b}{\Gamma\ (2+b)} > 1$

$$X = \frac{q\ t}{c+y}\left[\frac{1}{Bt^b\ \Gamma(2-b)} - \frac{1}{(Bt^b)^2\ \Gamma(2-2b)} + \frac{1}{(Bt^b)^3\ \Gamma(2-3b)} - \frac{1}{(Bt^b)^4\ \Gamma(2-4b)} + \ldots\ldots\ldots\right] \tag{2.14}$$

Surface Irrigation Automation

Automatic Structures

A structure can be classified as fully automatic or semiautomatic. Fully automatic structures usually use sensing devices located in the field or programmed timers to trigger their operation. A fully automatic gate will reset itself after the completion of one irrigation and be ready for the next. A semiautomatic gate will require manual resetting between irrigations. These gates are usually triggered by a mechanical timer.

Boundurant and Humpherys (1962) described some automatic structures of the check type which control the water level in farm distribution ditches. After checking the water level to a raised position for a predetermined time, the automatic gate releases, allowing the water to flow to the next set. Individual furrows or border strips receiving the water must be well graded so they may be irrigated without the farmer's attention. A timing or sensing device is required to trigger these automatic structures. The energy required to operate the structure itself is usually obtained from the flowing water. Automatic controls vary from simple alarm-clock-timer released checks to elaborate radio and electronically controlled structures with programmable timers or moisture-sensing devices.

Cutback streams from lined ditches can be obtained by constructing the ditch in a series of level bays with spile outlets at equal elevation along the side of the ditch. Water is released sequentially downstream from one bay to the next by timed check gates. As the water advances to the next check, the water level in the upper bay is lowered and flow from the upper bay outlets is reduced (Garton, 1966; Humpherys, 1971; Nicolaescu and Kruse, 1971; Hart and Borrelli, 1972; Evans, 1977).

Automatic Discharge Control

Higher water application efficiency may theoretically be obtained if the flow in a furrow is reduced or cutback after the water has reached the end of the field. This technique is difficult to employ in practice because of the time required to readjust the individual furrow streams and the difficulty in managing the surplus water. Structures and systems were developed to automatically reduce the flow of water to the furrow after a prescribed time interval (Garton, 1966).

Pneumatically operated and radio controlled valves were also developed to control the discharge from turnout structures (Haise et al., 1965). These valves control the discharge from alfalfa-type valves, an underground pipeline system or from turnouts in the farm ditches. The pneumatic valve for pipeline distribution systems is essentially an inflatable O-ring which when inflated forms an annular seal between the alfalfa valve seat and valve lid. The lay-flat pneumatic valve for ditch systems is a flat, rectangular tube that inflates to form a closure within the underground portion of the turnout pipe. Inflation and exhaustion of air from the valves is remotely controlled by a signal transmitted by wire or by radio from a centrally located timing device.

The most common gates for automatic control of open channel systems are the drop closed and drop open types. The drop closed gate is used to divert water directly onto irrigated fields or from one ditch into another. In the open position, it is suspended over a flow opening and, when tripped, falls by its own weight to stop the flow of water. Semiautomatic drop closed gates and dams tripped by mechanical timers are extensively used in New Zealand (Taylor,1965 ; Stoker, 1978).

The drop open gate is hinged so that when tripped, it either falls or swings open to allow water to flow downstream. Gates may be tripped by different actuating devices such as mechanical timers, solenoids, floats, or pneumatic and hydraulic cylinders. Gates of various configurations and design have been used by different investigators (Calder and Weston, 1966; Kinberlin, 1966; Humpherys, 1969; Hart and Borrelli, 1970; Lorimor, 1973; Evans, 1977; Haise et al., 1980).

Surge Flow Irrigation

Chow (1959) referred to a moving hydraulic jump due to an abrupt decrease or increase in flow, such as that caused by sudden closing or opening of a gate, as a surge.

Stringham and Keller (1979) first introduced the concept of surge flow furrow irrigation. The system they described used an automated gated pipe with a microprocessor control unit. The cutback capability was accomplished by reducing the time instead of the instantaneous flow rate into the furrow. Stringham and Keller concluded that most simple irrigation valves could be operated in an on-off mode quite effectively, but not in the fully-on, partially-off mode needed for cutback systems. In order to achieve the needed cutback flow they cycled the valves on and off in a manner that achieved a time averaged cutback flow without changing the instantaneous discharge of the valves. When the valves are open half the time and closed half the time the same average stream size is achieved as if half the flow runs full time. The cycle time can be variable. Three banks of four furrows, each 660 ft long were studied. Each bank supplied two wheel rows and two non-wheel rows (wheel rows refer to furrows compacted by tractor tires). The surge valves for all three banks were set to give a discharge of 13 gpm. The first bank had a constant rate until the water reached the end of the furrow. The second bank was cycled at a steady rate of 8 seconds on and 8 seconds off giving an average flow rate of 6.5 gpm. The third bank was cycled at a steady rate of 16 seconds on and 8 seconds off giving an average flow rate of 8.6 gpm. They reported that the advance time for the 16 sec on, 8 sec off, furrows was faster than the advance time for the steady flow in spite of the fact that the average stream flow was only about 67 percent as large. Furthermore, for the first 300 ft of furrow, the advance rate in all three operational modes was nearly the same even though the 8 sec on, 8 sec off flow regime had an average stream size of only 50 percent of the steady flow.

There have been two approaches to conducting surge flow experiments. The first approach was to use different instantaneous streams with different cycle ratios to give an equal quantity of water applied to each furrow over a given cycle time. The second approach was to use a constant stream with different cycle times and constant cycle ratios to give a time average stream equal to the continuous flow. The second approach eliminates the effects of using variable instantaneous flow rates on the advance rate.

Bishop et al. (1981) conducted field tests to study the effect of cycling furrow inflows on advance rates. They reported that the effects of surge flow irrigation were most apparent during the first irrigation. In the second irrigation the advantages of surge flow were substantially reduced. The difference between the continuous and surge flow treatments was significant and the differences among the surge flow treatments were not. In the second irrigation when infiltration differences were less noticeable in the field or when tractor wheel compaction reduces these differences mechanically, the advance under surge flow was much closer to the advance under continuous flow.

Walker et al. (1982) developed a flowing infiltrometer that measures furrow intake under conditions representative of actual field conditions. The extended Kostiakov equation was used to fit the field measurements. These investigators noticed a significant reduction in the opportunity time exponent and uncertain reduction in the basic intake rate. The number of tests run was too small to determine the specific differences between surged and continuous waterings. The effect of soil type on infiltration in surge flow was dependent on the stability of soil aggregates.

Podmore and Duke (1982) conducted a study of surge flow in furrow irrigated corn. Surge irrigation in furrows was achieved by equipping gated pipe with a pneumatically activated pillow valve for each furrow. The ratio of average steady state infiltration rates, derived from inflow and outflow measurements, for surge irrigation to that of continuous flow was approximately 0.5, indicating that surge irrigation had a significant impact on the infiltration process. A constant furrow inflow and cycle ratio of 50% duty and a variable cycle time was used. This procedure resulted in a more rapid advance for the continuous flow treatment since, in a given time, twice as much water was applied to the continuous flow treatment as compared to the surge treatments. In another experiment the continuous flow rate was reduced by 50% so that all treatments had the same average flow rate. In this case the surge flow treatments advanced slightly more rapidly than the continuous flow treatments. The reported irrigation efficiency for surge flow was lower or equal to that for continuous flow. The same gross application was used for all treatments. Since the surge treatments produced lower steady state infiltration rates, more runoff was produced when compared to continuous flow irrigation. Consequently, lower irrigation efficiencies resulted. No significant difference was reported for the surge flow and continuous flow treatments.

Podmore et al. (1983) switched surge irrigation applications to continuous flow at half the instantaneous inflow rate after about 75% of the furrows had completed advance. They concluded that surge irrigation with cutback after advance gave higher application efficiencies than either continuous flow or fully surged conditions. They suggested that the optimum surge system might begin an irrigation with short cycle times and increase the cycle times as the advance progressed.

A compelete analysis of border irrigation would require information on the effect of land slope, infiltration, roughness of soil surface, vegetation, and depth of water on the advance rate.