Surface Irrigation Modeling

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Surface Irrigation

- Surface irrigation is the oldest and most commonly used irrigation method in the world.
- Over 90% of the irrigated land in the world, which is about 16% of the total cultivable land, is irrigated by surface irrigation.
- In the United States, about 40% of the irrigated land is irrigated by surface irrigation.

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Surface Irrigation

- Advantages of Surface Irrigation
  - Low expenditure in energy
  - Minimum capital investment
  - Simple equipment

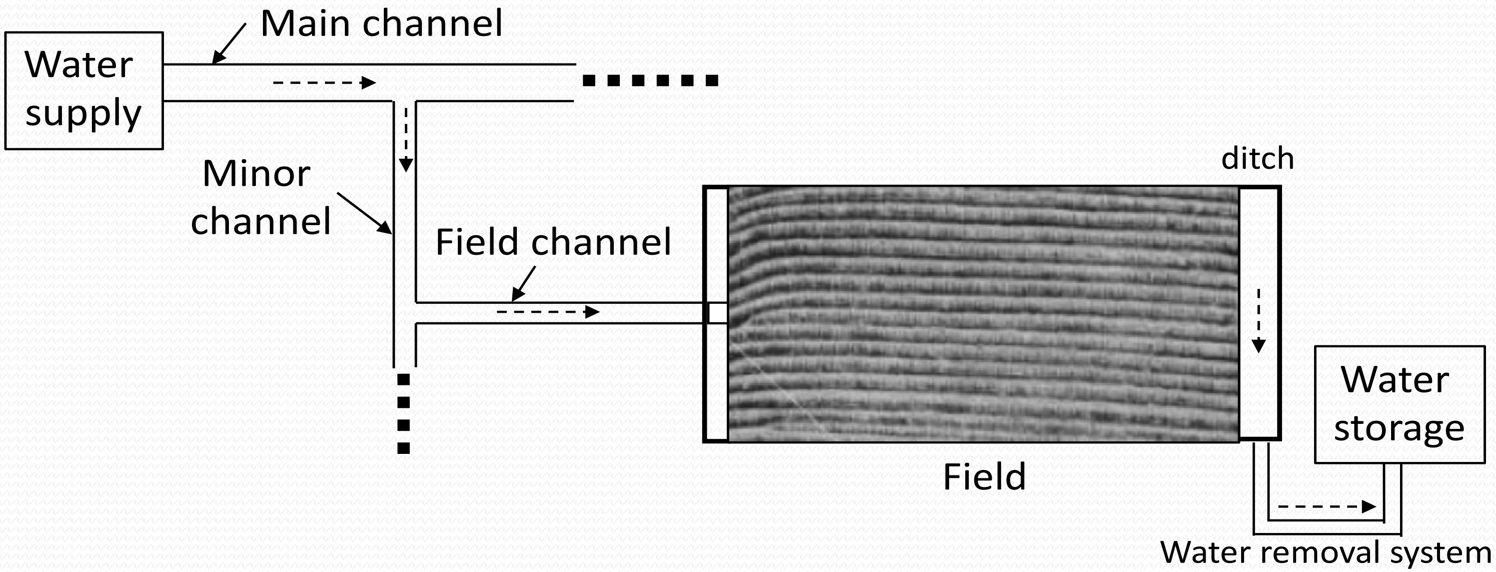
- Disadvantages of surface irrigation
  - Large labor input
  - Large stream size
  - Land leveling
  - Low efficiency

Surface Irrigation

- Methods of surface irrigation
  - Border irrigation
  - Basin irrigation
  - Water spreading
  - Furrow irrigation
  - Contour ditch irrigation

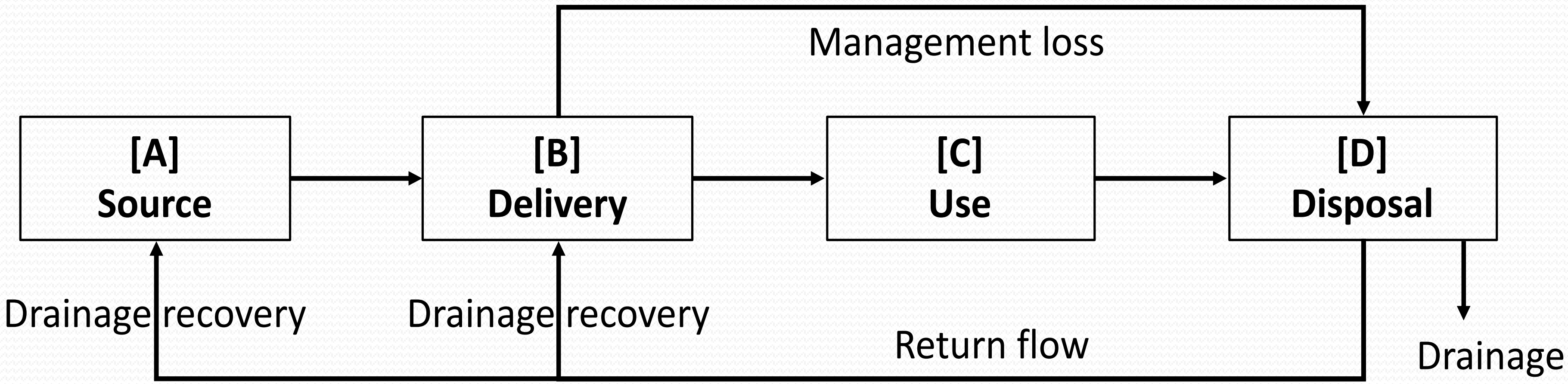
Irrigation: Physical System

- The physical system is comprised of four sub-systems; (1) water supply sub-system, (2) water delivery sub-system, (3) water use sub-system, and (4)water removal and recycle sub-system.
- The system may also have measuring devices and turnouts.



Components of a typical irrigation system

Physical System (Contd.)



[A] Storage dam, Open wells

[B] Primary canals, Distributed storage

[C] Farm ponds, Irrigated field

[D] Primary drains, Evaporation ponds

Different subsystems and their interconnections

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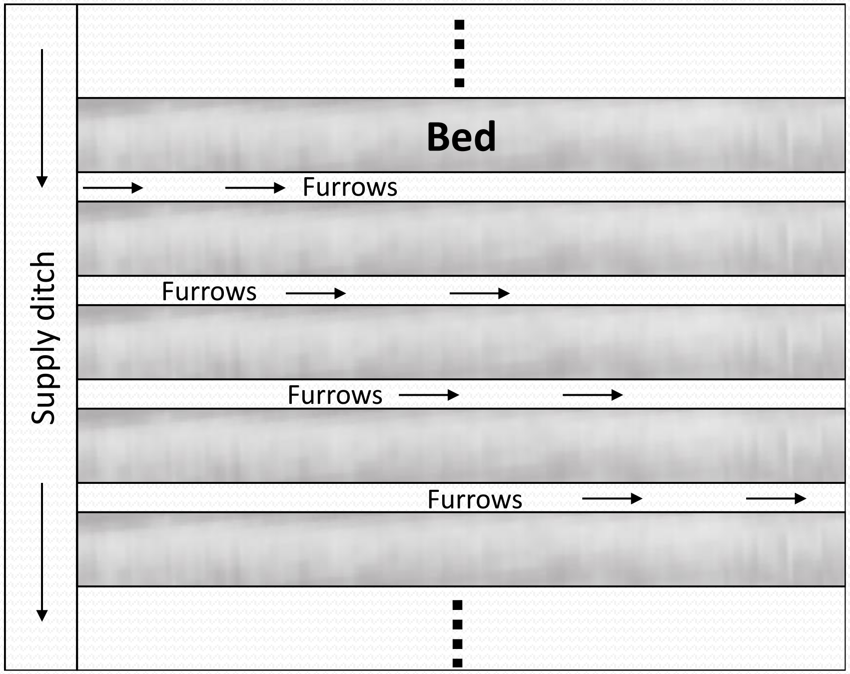
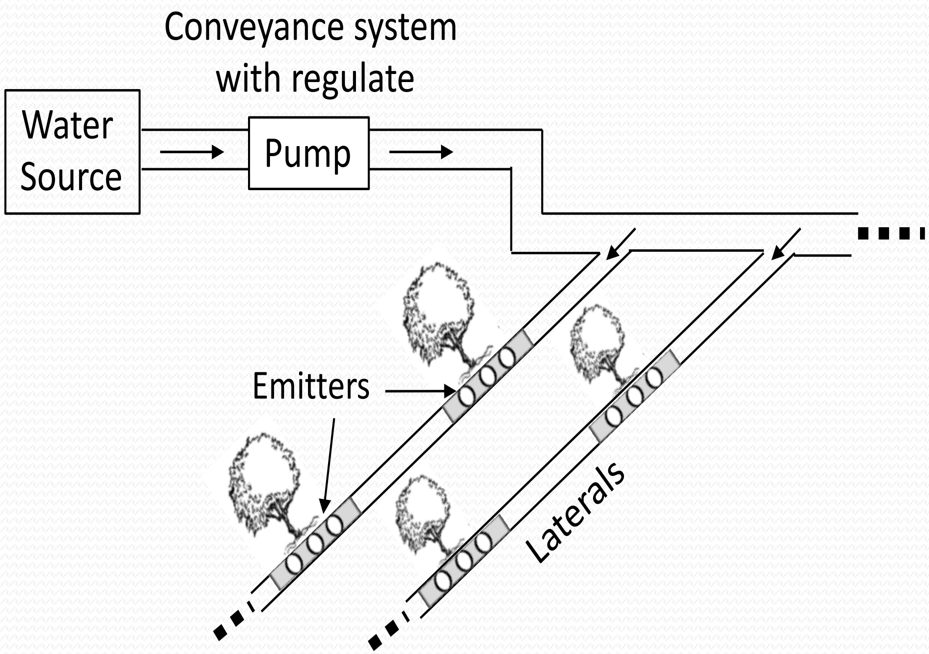
Irrigation methods

- There are four basic methods of water application for irrigation: (1) surface, (2) sprinkler, (3) trickle, and (4) below-surface.



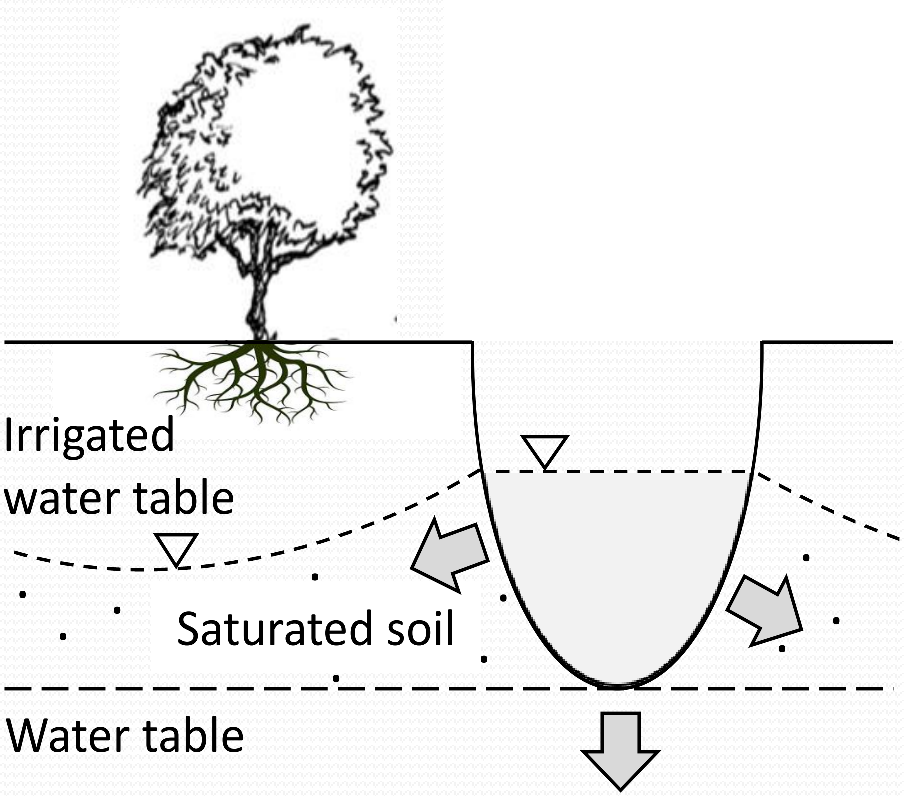
Furrow irrigation



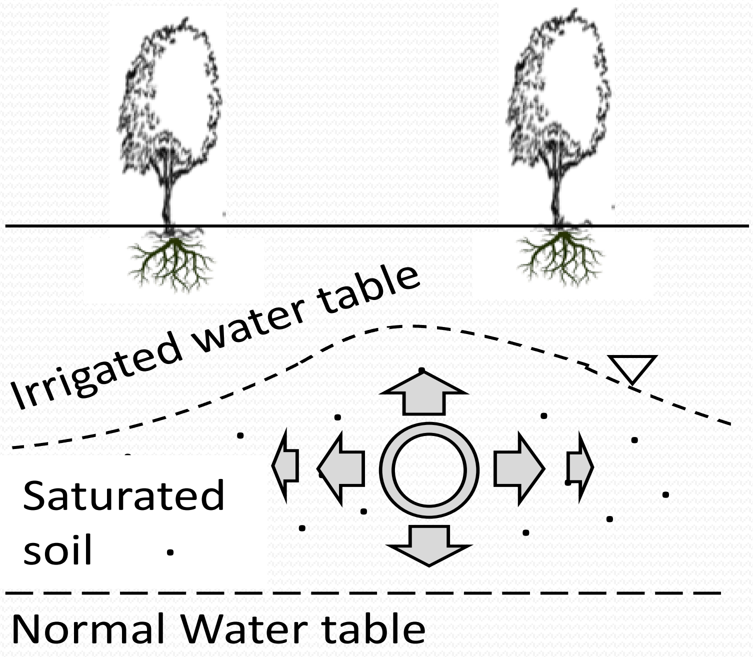
Trickle method of irrigation>

Irrigation methods (Contd.)

- The sub-irrigation method supplies water to the rootzone by artificially regulating the groundwater table elevation.



Sub-irrigation by open-ditch method



Sub-irrigation by underground perforated pipe method

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Surface Irrigation Methods

- Some irrigation methods can be classified based on land slope, because some methods are designed for level land and some for land with some slope.

- (1) Level System: This type of system is very popular in developing countries like India where land holdings are very small

- (2) Graded System: Graded systems can be classified as graded border, contour ditch, graded furrow, corrugation, and contour furrow.

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Choice of an Irrigation Method

- **1. Natural Factors (climate, soil texture, water capacity, slope)**
- **2. Crop type (water tolerance)**
- **3. Type of Technology (equipment, maintenance)**
- **4. Irrigation Practice (tradition of irrigation, farmer's decision)**
- **5. Labor (technical knowhow)**
- **6. Cost and Benefit (labor cost, operational cost)**
- **7. Selection of a Surface Irrigation Method (type of system, shape of field)**

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Surface Irrigation Decision Variables

- Objective:
  - Apply the required irrigation depth to replenish the soil moisture depletion in the crop root zone uniformly throughout the field while minimizing the loss of water due to deep percolation and runoff.
  - It is very difficult to uniformly apply water with high application efficiency, because a number of factors (parameters and variables) affect the performance of surface irrigation.
- Irrigation parameters
  - Factors that do not change during the irrigation event as well as during the season.
- Irrigation variables
  - They can change during an irrigation event and also in the season.

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Surface Irrigation Decision Variables

- The factors and variables can be grouped into three broad categories:
  - Field geometry
  - Field conditions
  - Management variables
- (1) Field geometry
  - It can be defined by length, width, slope, and shape of furrow
  - It is often fixed, which limits the length of furrows, basin or borders
  - In some cases the length can be considered as a design variable
  - The width of basin and borders is often dictated by the machinery width
  - Furrow spacing depends on agronomic considerations and furrow shape depends on the available farm equipment and local practices.

Surface Irrigation Decision Variables

- (2) Field conditions
  - Flow resistance is generally considered using Manning's roughness coefficient (*n*).
  - The roughness characteristics vary not only in space but also vary during the season.
  - Roughness is influenced by the growth of vegetation, surface sealing, tillage operation, and flow geometry.
  - For design of furrow irrigation, an *n* value of 0.04 is generally used.

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Table 1. Recommended Manning's '*n*" values for design of surface irrigation systems (from Jurriens et al. 2001)

n value	Field conditions	Irrigation Methods
0.04	Smooth, bare soil surface; row crops	Furrow, basin and border
0.10	Drilled, small-grain crops, drill rows in flow direction	Corrugation, basin and border
0.15	Alfalfa, mint, broadcast small grains	Basin and border
0.20	Dense alfalfa or alfalfa on long fields without secondary ditches	Basin and border
0.25	Dense sod crops and small grains, drilled perpendicular to flow direction	Basin and border

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Surface Irrigation Decision Variables

- Infiltration controls advance, infiltration, runoff and recession and thus affects the performance of surface irrigation and is a basic design variable
- Irrigation systems should be designed with field representative infiltration characteristics
  - Several infiltration equations have been developed like:
  - The Kostiakov equation:

$$Z = k\tau^a \qquad (1)$$

  - The modified Kostiakov (Kostiakov-Lewis) equation:

$$Z = k\tau^a + f_c\tau \qquad (2)$$

where Z = cumulative infiltration volume (m^3/unit area)

k = parameter (m/min^a)

a = fitted parameters, tau is the intake opportunity time (min)

f_c= basic infiltration rate (m/min).

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- Table 2. Kostiakov-Lewis infiltration parameters as a function of NRCS Soil Intake Number for first and later irrigations (from Walker, 2003; SIRMOD-III Manual) {Full table given in the notes}

NRCS Intake No	Soil Type	*k* (m^3/min^a)		*a*		f_c ($m^3/m/m/min$)	
		First Irrigation	Later Irrigations	First Irrigation	Later Irrigations	First Irrigation	Later Irrigations
.01	Heavy Clay	.0044	.0044	.200	.200	.000011	.000011
.05	Clay	.0043	.0043	.258	.258	.000022	.000022
.10	Clay	.0038	.0038	.317	.316	.000035	.000035
.15	Light clay	.0036	.0036	.257	.255	.000046	.000046
.20	Clay Loam	.0035	.0034	.388	.385	.000057	.000057
.25	Clay Loam	.0034	.0033	.415	.411	.000068	.000067

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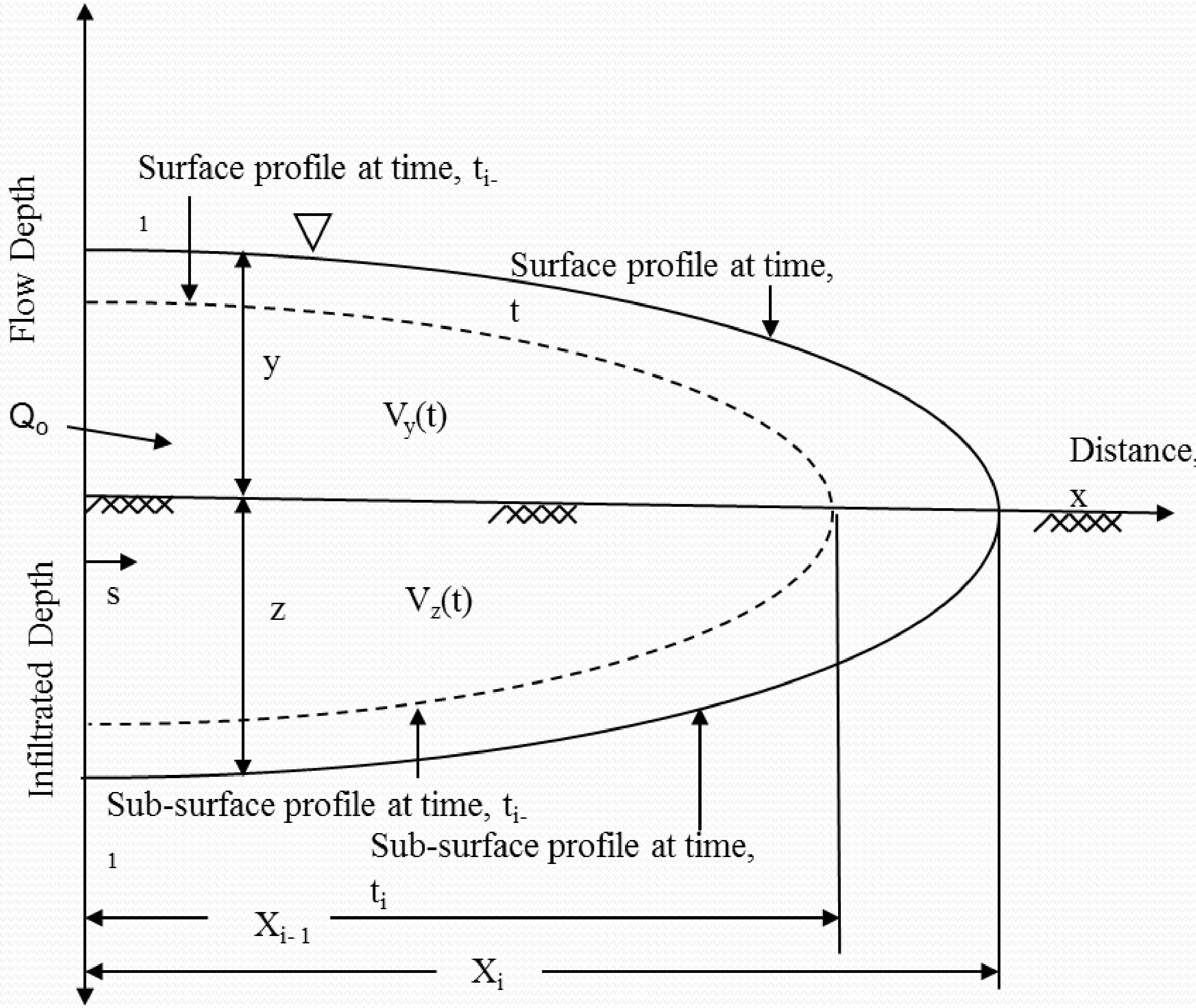
Surface Irrigation Decision Variables

- (3) Management variables
  - These include inflow rate, cutoff time, and required irrigation depth.
  - The required irrigation depth can be determined using irrigation scheduling.
  - The main task is to irrigate the field by choosing a suitable combination of the inflow rate and cutoff time to obtain better irrigation performance within the existing constraints.
  - Among all irrigation variables the inflow rate and time of cutoff offer the most flexibility to a decision maker.
  - This flexibility in inflow rate and cutoff time is related with the delivery system

Hydraulics of Surface Irrigation

- During surface irrigation, the hydraulics of flow changes with time and space.
- Different flow regimes develop at different times and spaces. However, the dominating flow regime that prevails over a majority of time can be characterized by gradually varied unsteady free surface flow.
- A typical change in water surface profile over a small time interval during the water advance.
- The flow is unsteady, because the flow rate and depth at each point increase with time due to the time-dependent intake characteristics of soil and it is non-uniform, because both flow rate and depth decrease gradually down the field.

Hydraulics of Surface Irrigation



Surface and sub-surface profiles at a small time increment during irrigation.

Hydraulics of Surface Irrigation (Contd.)

- The flow of water over the soil surface during surface irrigation can be characterized by St. Venant equations of continuity and momentum equations:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} + I = 0 \qquad (3)$$

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} = g(S_0 - S_f) + \frac{VI}{2A} \qquad (4)$$

where Q = flow rate (L^3/T or L^2/T in border irrigation

A = cross-sectional area of flow (L^2)

I = volume rate of infiltration per unit length of the channel or border (L/T),

V = average velocity in the flow cross-section (L/T)

g = gravitational acceleration (or ratio of weight to mass), (L/T^2),

Hydraulics of Surface Irrigation (Contd.)

y = flow depth (L)

S_o = channel bottom slope

S_f = channel friction slope

x = distance in the direction of flow (L)

t = time (T)

$g\partial y / \partial x$ = unbalanced hydrostatic pressure force on the surface water,

S_o = component of the gravitational force in the direction of flow

S_f = slope of the energy grade line or hydraulic drag

$V\partial V / \partial x$ = local acceleration (a measure of unsteadiness),

$V\partial V / \partial x$ = convective acceleration (a measure of non-uniformity)

$(VI)/(2A)$ = net acceleration stemming from the removal of zero-velocity components of the surface stream at the bed by infiltration.

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Hydraulics of Surface Irrigation (Contd.)

- Equations (3) and (4) are based on the following assumptions:
  - The fluid is incompressible; i.e., the density of water is constant
  - The flow is one-dimensional
  - Pressure is hydrostatic
  - The streamline curvature is small
  - The bottom slope of the channel is small.

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Hydraulic Surface Irrigation Models

- A number of surface irrigation models have been developed based on simplified forms of the St. Venant equations like
  - Zero-inertia
  - Kinematic-wave
- Zero-inertia
  - It neglects the inertial and acceleration terms in equation (4):

$$\frac{\partial y}{\partial x} = S_0 - S_f \qquad (5)$$

  - Because flow velocities during most surface irrigations are low and hence accelerations are small and can be neglected.
  - Surface irrigation models based on equations (3) and (5) are called zero-inertia models.
  - The zero-inertia models have been found to yield results as accurate as full hydrodynamic models.

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Hydraulic Surface Irrigation Models (Contd.)

- Kinematic-wave
  - It is obtained by neglecting the water depth gradient term in equation (5) that reduces the momentum equation to:

$$S_0 = S_f \qquad (6)$$

  - This simplification is reasonable if the bottom slope is sufficiently steep.
  - Equations (3) and (6) constitute the basis of kinematic wave models.
  - Equation (6) can be expressed as a relationship between depth and discharge, such as Manning's or Chezy's equation.
  - The kinematic wave models have limited application to sloping and free draining conditions.
  - kinematic wave solutions may not be suitable for borders with zero or small slope or blocked borders. kinematic-wave models accurately simulate surface irrigation processes for steep slopes.

Hydraulic Surface Irrigation Models

- The volume balance equation for any time (t) can be expressed as:

$$Q_0 t = V_y(t) + V_z(t) \qquad t < T_a \qquad (7)$$

where Q_o = steady inflow rate (m^3/min)

t = time since the beginning of irrigation (min)

T_a = advance time (min)

V_y = volume of surface storage at time t (m^3)

V_z = volume of infiltrated water at time t (m^3).

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Volume Balance Irrigation Models

- The volume of surface storage at any time *t* over the advance distance can be determined by integrating the flow area as:

$$V_y(t) = \int_0^x A(s,t)\,ds = \bar{A}\,x = \sigma_y A_0 x \qquad (8)$$

where A = cross-sectional area of flow;

$\bar{A}$ = is the average flow cross-sectional area; σ_y is the surface shape factor (varying between 0.70 and 0.80, but often taken as 0.77)

s = variable of integration

A_o = inlet area related to the normal depth corresponding to the inflow rate, roughness, field slope and hydraulic radius at the field inlet

  - A_o can be expressed as: $$A_0 = \left(\frac{Q_0^2 n^2}{3600\,\rho_1 S_0}\right)^{1/\rho_2} \qquad (9)$$

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Volume Balance Irrigation Models (Contd.)

where Q_o = inflow rate (m3/min/unit width)

n = Manning's roughness coefficient

S_o = field slope

ρ_1 and ρ_2 = the empirical shape factors

- If there exists a level slope condition (e.g., basin), the friction slope in Manning's equation is assumed to equal the inlet flow depth (y_o) divided by the advance front distance (x)
- Then equation (9) becomes:

$$A_0 = y_0 = \left(\frac{Q_0^2 n^2 x}{3600} \right)^{0.24} \tag{10}$$

- The surface area varies from A_o at the field inlet to zero at the advancing tip.

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Volume Balance Irrigation Models (Contd.)

- The volume balance approach neglects the space-time variation of *A* and assumes a constant average area.
- The infiltrated volume over the advance distance at any time *t* can be determined as follows:

$$V_z(t) = \int_0^x Z(s,t)\,ds = \int_0^x Z(t - t_s)\,ds = \sigma_z Z_0 x \tag{11}$$

where Z = infiltrated volume per unit area

$t - t_s$ = intake opportunity time

t_s = time when water front reaches the distance, *s*

Z_o = infiltrated volume per unit area at the field inlet

σ_z = sub-surface shape factor (the ratio of infiltrated volume over the distance *s* to infiltrated volume at the field inlet)

- It is assumed that $Z(s, t)$ is not a function of water surface depth but is dependent on intake opportunity time.

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Volume Balance Irrigation Models (Contd.)

- Substituting the volume of surface storage [equation (8)] and the volume of infiltration [equation (11)] terms into equation (7), one obtains the Lewis-Milne (1938) volume balance equation:

$$Q_0 t = \overline{A} x + \int_0^x Z(t - t_s) ds = \sigma_y A_0 x + \sigma_z Z_0 x \qquad (12)$$

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Power Advance Volume Balance Model

- The solution techniques used for solving equation (12) can be grouped into four categories:
  - Numerical or recursive approach
  - Kernel function approach
  - Laplace transformation
  - Power advance approach
- The integral term in equation (12) is a distance integral of a time dependent function
- Power advance approach
  - It assumes the following functional relationship between the advance rate and time:

$$X = p t_x^r \tag{13}$$

Power Advance Volume Balance Model (Contd.)

in which X = advance distance for the basin, border or furrow (m),

t_x = advance time to distance x since the beginning of irrigation (min)

p and r = fitted parameters.

- Using the power advance given by equation (13) along with the modified Kostiakov infiltration equation [equation (12)]:

$$Q_0 t_x = \sigma_y A_0 X + \sigma_z X k t_x^a + \sigma_z' f_c t_x X \qquad (14)$$

in which Q_o = inflow rate (m^3/min),

A_o = cross-sectional area of flow at the inlet (m^2)

X = advance distance (m)

t_x = advance time to distance x since beginning of irrigation (min)

k and a = coefficients of the modified Kostiakov equation

Power Advance Volume Balance Model (Contd.)

f_c = basic infiltration rate ($m^3/m/min$)

p and r = empirical parameters of the advance curve

σ_y = surface storage factor

- $\sigma_z^{'}$ can be defined as: $\sigma_z = \dfrac{a + r(1-a) + 1}{(1+a)(1+r)}$ (15)

$$\sigma_z^{'} = \frac{1}{1+r} \qquad (16)$$

- Equation (14) can be used to either determine the modified Kostiakov infiltration parameters using the advance distance and time information at two points along the field or advance to the end of the field knowing infiltration parameters
- This method is also known as "two-point method."

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Evaluation of Infiltration Parameters

- The two points most often correspond to the half of the field length (L/2) and the field length (L).
- By substituting these pairs in equation (14) one can obtain two volume balance equations corresponding to a half field length and full field length:

$$Q_0 t_{L/2} = \sigma_y A_0 \frac{L}{2} + \sigma_z k t_{L/2}^a \frac{L}{2} + \sigma_z^{'} \frac{f_0 t_{L/2} L}{2} \qquad (17)$$

$$Q_0 t_L = \sigma_y A_0 L + \sigma_z k t_L^a L + \sigma_z^{'} f_0 t_L L \qquad (18)$$

  - Multiplying equation (17) by 2/L throughout, one denotes :

$$V_{L/2} = \frac{2Q_0 t_{L/2}}{L} - \sigma_y A_0 - \sigma_z^{'} f_0 t_{L/2} \qquad (19)$$

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Evaluation of Infiltration Parameters (Contd.)

- Equation (17) can be expressed as:

$$\sigma_Z k t_{L/2}{}^{a} = V_{L/2} \quad \text{or} \quad a\ln(t_{L/2}) + \ln\sigma_Z + \ln k = \ln(V_{L/2}) \qquad (20)$$

- By dividing equation (18) by L throughout:

$$V_L = \frac{Q_0 t_L}{L} - \sigma_y A_0 - \sigma_z^{'} f_0 t_L \qquad (21)$$

- Thus, equation (18) can be expressed as:

$$\sigma_Z k t_L{}^{a} = V_L \quad \text{or} \quad a\ln(t_L) + \ln k + \ln\sigma_Z = \ln(V_L) \qquad (22)$$

- From equations (20) and (22), constant "*a*" can be obtained as:

$$a = \frac{\ln\left(V_L / V_{L/2}\right)}{\ln\left(t_L / t_{L/2}\right)} \qquad (23)$$

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Evaluation of Infiltration Parameters (Contd.)

- k can be obtained as:

$$k = \frac{(1+a)(1+r)V_L}{[a+r(1-a)+1]t_L^a} \qquad (24)$$

- The two-point method does not estimate the basic infiltration rate (f_c), which is generally determined using information on inflow and outflow as:

$$f_c = \frac{Q_0 - Q_r}{L} \qquad (25)$$

where Q_0 and Q_r = inflow and runoff (outflow) rates, respectively (m^3/min)

L = length of the field (m).

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THANK YOU

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