2. DESIGN OF SURFACE IRRIGATION SYSTEMS

- Introduction to Surface Irrigation Systems
- Main glossary in irrigation methods
- Surface Irrigation Methods
- Criteria for Selection of Various Methods
- Hydraulic Design of Surface Irrigation System
  - Wild Flooding Irrigation (mainly practiced in Ethiopia)
  - Furrow Irrigation System Design
  - Basin Irrigation System Design
  - Border Irrigation System Design

2.1. Introduction to Surface Irrigation System

The term 'surface irrigation' refers to a broad class of irrigation methods in which water is distributed over the field by overland flow. A flow is introduced at one edge of the field and covers the field gradually. The rate of coverage (advance) is dependent almost entirely on the differences between the discharge onto the field and the accumulating infiltration into the soil. Secondary factors include field slope, surface roughness, and the geometry or shape of the flow cross-section.

Surface irrigation offers a number of important advantages at both the farm and project level. Because it is so widely utilized, local irrigators generally have at least minimal understanding of how to operate and maintain the system. In addition, surface systems are often more acceptable to agriculturalists who appreciate the effects of water shortage on crop yields since it appears easier to apply the depths required to refill the root zone. The second advantage of surface irrigation is that these systems can be developed at the farm level with minimal capital investment. Also they are less affected by climatic and water quality characteristics.

Although they need not be, surface irrigation systems are typically less efficient in applying water than either sprinkler or trickle systems. Many are situated on lower lands with heavier soils and, therefore, tend to be more affected by water logging and soil salinity if adequate drainage is not provided. The need to use the field surface as a conveyance and distribution facility requires that fields be well graded if possible. Land levelling costs can be high so the surface irrigation practice tends to be limited to land already having small, even slopes.

Irrigation systems generally consist of four components:

1) Physical systems
2) Social and organizational systems
3) Cropping system
4) Economic systems

This chapter deals in depth with the considerations that should be taken in the design of the physical system in general and in particular the water use sub-system. The primary
The purpose of the physical system is to supply water to an area for crop production. The physical systems of Surface irrigation systems as a whole consist of four subsystems.

These are:

1) The water supply subsystem
2) The water delivery subsystem
3) The water use subsystem
4) The water removal subsystem

i) Water delivery system

The function of water delivery sub-system is to convey water from the source to field through main canal, distributaries, minors and field channels, at constant, regulated rate, at proper elevation, with seepage controlled, with out excessive erosion or sediment taken, with appropriate water quality and amount.

ii) Water supply sub-systems

The output from water delivery sub-system is the input for water application sub-system.

Functions: -
- To distribute the desired amount of water with the designed uniformity over the field.
- To satisfy erosion control standards
- To provide necessary surface drainage

iii) Water use sub-system

The water use sub-system receives water from the application sub-system.

Functions: -
- To supply the water requirement of the crop.
- To maintain acceptable level of soil salinity.
- To ensure adequate nutrients.
- To provide soil conditions for supporting plants, preventing soil crusting facilitating tillage etc

iv) Water removal sub-system

This sub-system is used for removal and disposal of surface and sub-surface waters from land to improve agriculture operations.

Functions: -
- To provide proper root aeration by lowering ground water table,
- To maintain appropriate salinity levels with in the soil profile,
- To dispose (remove) excess irrigation or rain water from the field.
A surface irrigation event is composed of four phases as illustrated graphically in Figure 2.2. When water is applied to the field, it 'advances' across the surface until the water extends over the entire area. It may or may not directly wet the entire surface, but all of the flow paths have been completed. Then the irrigation water either runs off the field or begins to pond on its surface. The interval between the end of the advance and when the inflow is cut off is called the wetting or ponding phase. The volume of water on the surface begins to decline after the water is no longer being applied. It either drains from the surface (runoff) or infiltrates into the soil. For the purposes of describing the hydraulics of the surface flows, the drainage period is segregated into the depletion phase (vertical recession) and the recession phase (horizontal recession). Depletion is the interval between cut off and the appearance of the first bare soil under the water. Recession begins at that point and continues until the surface is drained.

Summarising the four distinct hydraulic phases of surface irrigation system:

1. **Advance phase**: the time interval between the start of irrigation and arrival of the advancing (wetting) front at the lower end of the field.
2. **Ponding (wetting storage or continuing) phase**: the irrigation time extending between the end of advance and inflow cutoff. The term “Wetting” phase is usually used for furrow and border where tail water runoff can occur, whereas ponding is the preferred term for basin irrigation (no tail water runoff).

3. **Depletion (vertical recession) phase**: the time interval between supply cut-off and the time that water dries up at the inlet boundary.

4. **Recession (horizontal recession) phase**: the time required for the water to recede from all points in the channel, starting from the end of the depletion phase. The time difference at each measuring station between the clock time or cumulative time for advance and recession is the opportunity time, $T$, infiltration to occur.

5. **Cut off time (tco)**: Cumulative time since the initiation of irrigation until the inflow is terminated.

6. **Cutback irrigation**: The practice of using a high unit discharge during the advance phase and a reduced one during the wetting or ponding phase to control runoff.

7. **Opportunity time ($\tau$ req)**: The cumulative time between recession and advance at a specific point on the surface irrigated field. Usual units are minutes or hours.

---

**Figure 2.2**: Time-space trajectory of water during a surface irrigation showing its advance, wetting, depletion and recession phases.
The time and space references shown in Figure 2.2 are relatively standard. Time is cumulative since the beginning of the irrigation, distance is referenced to the point water enters the field. The advance and recession curves are therefore trajectories of the leading and receding edges of the surface flows and the period defined between the two curves at any distance is the time water is on the surface and therefore also the time water is infiltrating into the soil.

It is useful to note here that in observing surface irrigation one may not always observe a ponding, depletion or recession phase. In basins, for example, the post-cut off period may only involve a depletion phase as the water infiltrates vertically over the entire field. Likewise, in the irrigation of paddy rice, irrigation very often adds to the ponded water in the basin so there is neither advance nor recession - only wetting or ponding phase and part of the depletion phase. In furrow systems, the volume of water in the furrow is very often a small part of the total supply for the field and it drains rapidly. For practical purposes, there may not be a depletion phase and recession can be ignored. Thus, surface irrigation may appear in several configurations and operate under several regimes.

### 2.2. Surface Irrigation Methods

Surface irrigation system for the specific needs will be considered with the following factors:

- costs of the system and its appurtenances,
- field sizes and shapes,
- soil intake and water holding characteristics,
- the quality and availability (timing of deliveries, amount and duration of delivery) of the water supply,
- climate,
- cropping patterns,
- historical practices and preferences, and
- accessibility to precision land levelling services.

**Wild Flooding**

There are many cases where croplands are irrigated without regard to efficiency or uniformity. These are generally situations where the value of the crop is very small or the field is used for grazing or recreation purposes. Small land holdings are generally not subject to the array of surface irrigation practices of the large commercial farming systems. Also in this category are the surface irrigation systems like check-basins which irrigate individual trees in an orchard, for example. While these systems represent significant percentages in some areas, they will not be discussed in detail in this paper. The evaluation methods can be applied if desired, but the design techniques are not generally applicable nor need they be since the irrigation practices tend to be minimally managed.
Fig. 2.3 Wild Flooding

**Basin Irrigation**

Basin irrigation is the most common form of surface irrigation, particularly in regions with layouts of small fields. If a field is level in all directions, is encompassed by a dyke to prevent runoff, and provides an undirected flow of water onto the field, it is herein called a basin. A basin is typically square in shape but exists in all sorts of irregular and rectangular configurations. It may be furrowed or corrugated, have raised beds for the benefit of certain crops, but as long as the inflow is undirected and uncontrolled into these field modifications, it remains a basin.

There are few crops and soils not amenable to basin irrigation, but it is generally favoured by moderate to slow intake soils, deep-rooted and closely spaced crops. Crops which are sensitive to flooding and soils which form a hard crust following irrigation can be basin irrigated by adding furrowing or using raised bed planting. Reclamation of salt-affected soils is easily accomplished with basin irrigation and provision for drainage of surface runoff is unnecessary.
Basin irrigation has a number of limitations, two of which, already mentioned, are associated with soil crusting and crops that cannot accommodate inundation. Precision land levelling is very important to achieving high uniformities and efficiencies. Many basins are so small that precision equipment cannot work effectively. The perimeter dykes need to be well maintained to eliminate breaching and waste, and must be higher for basins than other surface irrigation methods. To reach maximum levels of efficiency, the flow per unit width must be as high as possible without causing erosion of the soil. When an irrigation project has been designed for either small basins or furrows and borders, the capacity of control and outlet structures may not be large enough to improve basins.

The flow rate must be large enough to cover the entire basin approximately 60 to 75 percent of the time required for the soil to absorb the desired amount of water.

Basin irrigation can be used to apply prescribed application depths at design efficiencies of more than 90%. However, studies on basin irrigation systems in various countries have documented both extensive over and under-irrigation as the norm, which has resulted in overall low irrigation efficiencies.

Basin irrigation is suited to different crops, such as, rice, cotton, groundnuts etc. and to soils of moderate to low intake rate (50 mm/h or less) having smooth, gentle and uniform land slopes. The method is especially adapted to irrigation of grain and fodder crops in heavy soils where water is absorbed very slowly and is required to stand for a relatively long time to ensure adequate irrigation.
Border irrigation can be viewed as an extension of basin irrigation to sloping, long rectangular or contoured field shapes, with free draining conditions at the lower end. Figure 2.6 illustrates a typical border configuration in which a field is divided into sloping borders. Water is applied to individual borders from small hand-dug checks from the field head ditch. When the water is shut off, it recedes from the upper end to the lower end. Sloping borders are suitable for nearly any crop except those that require prolonged ponding. Soils can be efficiently irrigated which have moderately low to moderately high intake rates but, as with basins, should not form dense crusts unless provisions are made to furrow or construct raised borders for the crops. The stream size per unit width must be large, particularly following a major tillage operation, although not so large for basins owing to the effects of slope. The precision of the field topography is also critical, but the extended lengths permit better levelling through the use of farm machinery.
Border irrigation makes use of parallel earth rides to guide a sheet of flowing water across a field. The land between two levees is called a border strip, simply called a border. Border strips, like basins, can be described as rectangular channels (narrow or wide) in which the width of flow plays a dominant role in affecting the geometric elements of the channel. The border strip may vary from 3 to 30 meters in width and from 100 to 800 meters in length. Border irrigation is a more controlled version of wild flooding with additional field ditches that serve as supply sources for applying water to the field.

Border irrigation is generally well suited to soils with moderately high intake rates and to slopes less than 0.5 percent. The method can be classified as straight or contour borders depending on weather the borders are running along or across the main slope.

Borders can be grouped into three major categories depending on the management strategy adopted:

Fixed flow: a system in which the inlet flow rate remains constant throughout the duration of irrigation, the method is simple and less expensive but generally of low efficiency.

Cutback: this is a system in which irrigation begins with a maximum or near maximum non erosive inlet flow rate, which continues for a part of the irrigation period and then reduced to a level just above what is needed to wet the entire length of the border.

Tail water reuse: this is a system in which excess surface runoff from the downstream end is collected in a sump and then pumped back into the same field to open up more borders or used to irrigate another field.

Field application efficiency is good to excellent if the border strips are designed and installed properly and good water management practices are followed. Design water application efficiencies of the order 70 -75 % can be attained for slopes of 0.001 to 0.002 m/m on soils of silty clay to clay with depth of application of 75 - 100 mm. For high efficiencies, the stream size and the resulting rate of advance must be controlled to match the recession conditions to provide approximately equal infiltration opportunity time at both the upper and lower ends.

Figure 2.7: Border Irrigation
Furrow Irrigation

Furrow irrigation avoids flooding the entire field surface by channelling the flow along the primary direction of the field using ‘furrows,' 'creases,' or 'corrugations'. Water infiltrates through the wetted perimeter and spreads vertically and horizontally to refill the soil reservoir. Furrows are often employed in basins and borders to reduce the effects of topographical variation and crusting. The distinctive feature of furrow irrigation is that the flow into each furrow is independently set and controlled as opposed to furrowed borders and basins where the flow is set and controlled on a border by border or basin by basin basis.

Furrows provide better on-farm water management flexibility under many surface irrigation conditions. The discharge per unit width of the field is substantially reduced and topographical variations can be more severe. A smaller wetted area reduces evaporation losses. Furrows provide the irrigator more opportunity to manage irrigations toward higher efficiencies as field conditions change for each irrigation throughout a season. This is not to say, however, that furrow irrigation enjoys higher application efficiencies than borders and basins.

There are several disadvantages with furrow irrigation. These may include: (1) an accumulation of salinity between furrows; (2) an increased level of tail water losses; (3) the difficulty of moving farm equipment across the furrows; (4) the added expense and time to make extra tillage practice (furrow construction); (5) an increase in the erosive potential of the flow; (6) a higher commitment of labour to operate efficiently; and (7) generally furrow systems are more difficult to automate, particularly with regard to regulating an equal discharge in each furrow. Figure 4.5 shows two typical furrow irrigated conditions.
(b) Contour furrows

Figure 2.8: Furrow irrigation configurations (after USDA-SCS, 1967)

Figure 2.9 Typical furrow cross-section (wetting Pattern)
When properly designed and operated, furrow irrigation systems may result in a good performance. The wide variations in furrow cross-section types as well as the two dimensional nature of the infiltration process under furrow irrigation complicates mathematical analysis and field measurement needed to quantify irrigation parameters compared to other two methods.

Efforts to achieve high application efficiencies for furrow-irrigated systems are limited by very large spatial and temporal variation in infiltration characteristics. Thus, while efficiencies of 85 to 90 % are periodically reported from studies incorporating careful soil moisture monitoring and automation, efficiencies in the order of 50 to 70 % are more common. Moreover, designs could be acceptable if the water application efficiency is greater than 70 percent, with less than 10 percent deep percolation and 20 percent runoff losses, while storage efficiency is greater than 85 to 90 percent.

Most crops would be irrigated by the furrow method and is best suited to medium to moderately fine textured soils with relatively high water holding capacity and conductivity which allow significant water movement in both the horizontal and vertical directions. Like border irrigation, furrow irrigation systems, can be grouped into fixed flow, cutback flow and tail-water reuse system depending on the management strategy adopted.

2.3. Criteria for the selection of the various methods

The choice of irrigation system is frequently determined by certain limiting conditions that preclude one or another of the possibilities and may leave no alternative. The important factors that should be taken into account when determining which surface irrigation method is most suitable: basin, border or furrow irrigation are natural circumstances (slope, soil type), type of crop, required depth of application, level of technology, previous experiences with irrigation, required labor input. Moreover the irrigation system for a field must be compatible with the existing farming operations, such as land preparation, cultivation, and harvesting practices.

Natural circumstances

Flat lands, with a slope of 0.1 % or less, are best suited for basin irrigation: little land leveling will be required. Furrow irrigation can be used on flat lands (short, near horizontal furrows), and on mildly sloping land with a slope of maximum 0.5 %. A minimum slope of 0.05 % is recommended to assist drainage.

Border irrigation can be used on sloping land up to 2 % on sandy soil and 5 % on clay soil. A minimum slope of 0.05 % is recommended to ensure drainage. Generally, surface irrigation may be difficult to use irregular slopes, as considerable land leveling may be required to achieve the required land gradients.

Type of crop

Paddy rice is always grown in basins. Those crops that cannot stand a very wet soil for more than 12-24 hours should not be grown in basins. Furrow irrigation is best suited for irrigating row crops such as maize, vegetables and trees. Border irrigation is particularly
suitable for close growing crops such as small grains (sesame) and forage crops (alfalfa), but border irrigation can be used for row crops and trees.

**Required depth of irrigation application**

When the irrigation schedule has been determine, it is known how much water has to be given per irrigation application It must be checked that this amount can be indeed be given, with the irrigation method under consideration. Field experience has shown that most water can be applied per irrigation application when using basin irrigation, less with border irrigation and least with furrow irrigation. In practice in small-scale irrigation projects, usually 40 –70 mm of water are applied in basin irrigation, 30 – 60 mm in border irrigation and 20 – 50 mm in furrow irrigation. If, on the other hand, a large amount of irrigation water is to be applied per application, e.g. on clay soil and with a deep rooting crop, border or basin irrigation would be more appropriate.

**Level of technology**

Basin irrigation is the simplest of the surface irrigation methods. Especially if the basins are small, they can be constructed by hand or animal traction. Their operation and maintenance is simple. Furrow irrigation with the possible exception of short, level furrows requires accurate grading. Machines often do this. The maintenance ploughing and furrowing is often done by machines. This requires skill, organization and frequently the use of foreign currency for fuel, equipments and spare parts. Borders require the highest level of sophistication. They are constructed and maintained by machines. The grading needs to be accurate. Machine operation requires a high level of skill, organization and usually foreign currency.

**Required labor inputs**

The required labor inputs for construction and maintenance depend heavily on the extent to which machinery is used. In general it can be stated that to operate the system, basin irrigation requires the least labor and least skill. For the operation of furrow and border irrigation systems more labor is required combined with more skill.
Table 1 Differences and similarities of the three primary surface irrigation systems.

<table>
<thead>
<tr>
<th>Item</th>
<th>Furrow</th>
<th>Border</th>
<th>Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main slope</td>
<td>&lt; 1 % (min. 0.05%)</td>
<td>Up to 2-5 % (min. 0.05%)</td>
<td>Usually zero slope or nearly zero attained</td>
</tr>
<tr>
<td>Soils</td>
<td>Best suited to soils with moderate to low intake rates.</td>
<td>moderately low to moderately high intake rate soils</td>
<td>medium to fine textured soils</td>
</tr>
<tr>
<td>Infiltration</td>
<td>two dimensional</td>
<td>same as basin</td>
<td>one dimensional and vertically downward</td>
</tr>
<tr>
<td>Field size</td>
<td>large</td>
<td>large</td>
<td>All size</td>
</tr>
<tr>
<td>Geometry / shape of farm</td>
<td>regular</td>
<td>regular</td>
<td>all shape</td>
</tr>
<tr>
<td>Sediment load</td>
<td>not problematic</td>
<td>not problematic</td>
<td>not problematic</td>
</tr>
<tr>
<td>Biological quality</td>
<td>not problematic</td>
<td>not problematic</td>
<td>not problematic</td>
</tr>
<tr>
<td>Salinity</td>
<td>problem if very high salt</td>
<td>slightly problematic</td>
<td>not problematic</td>
</tr>
<tr>
<td>Crops variety</td>
<td>best for row crops</td>
<td>best for close growing crops</td>
<td>all crops but best for ponded water crops</td>
</tr>
<tr>
<td>Farming machinery</td>
<td>adapted to mechanized farming</td>
<td>easy to apply</td>
<td>difficult to use</td>
</tr>
<tr>
<td>Labor input</td>
<td>high</td>
<td>high</td>
<td>least labor compared to other surface irrigation systems</td>
</tr>
<tr>
<td>Application efficiency</td>
<td>60- 70%</td>
<td>60- 70 %</td>
<td>65 –80 %</td>
</tr>
<tr>
<td>Efficiency and uniformity</td>
<td>Relatively low</td>
<td>High with blocked ends</td>
<td>High</td>
</tr>
<tr>
<td>Level of technology</td>
<td>lower than border</td>
<td>highest</td>
<td>simplest</td>
</tr>
<tr>
<td>Initial cost</td>
<td>low to medium</td>
<td>lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Principal risk</td>
<td>Erosion</td>
<td>Scalding</td>
<td>Scalding</td>
</tr>
</tbody>
</table>

2.4. Hydraulic design of Surface Irrigation Systems

The design of a surface irrigation system first involves assessing the general topographic conditions, soils, crops, farming practices anticipated and farm operators’ desires and finance for the field or farm in question. Moreover, the first priorities in agriculture today is the development of irrigation design that are more efficient in the use of both water and energy resources for the varieties of crops and farming practices.

One of the purposes of design of surface irrigation systems is to facilitate operational practices so that the system can be managed and operated according to the plan and the desired goal can be achieved.

Surface irrigation systems are designed and operated to supply the individual irrigation requirements of each field on the farm while controlling deep percolation, runoff, evaporation and operational losses. Beside this, the objective of any water application is to
uniformly replenish the root zone moisture with enough percolation for the effective leaching of harmful salts.

Properly designed and operated surface irrigation systems can enhance crop yields. Often, however, inadequate design and management result in excessive water losses through deep percolation and/or tail water runoff. It can be also stated that high efficiencies are not generally attained with surface methods unless design, operation and management are of a higher standard and distribution. Despite the fact that surface irrigation is the most widely practiced method of irrigation and feasible under many circumstances, its low energy requirements and simplicity of operation, it is not only a major consumer of water but also one of the most inefficient users of water.

For example, the annual project efficiencies of some selected 16 countries (world wide, by FAO, 1998) ranges from 13 % (Saldana in Colombia) to 99 % (Tadla in Morocco). Similarly, the overall efficiency of state farms in the Middle Awash was about 40 % (1986). Generally, FAO (1995) pointed out that only 40% to 60% of the water is effectively used by the crop, the reminder of the water is lost in the system, in the farm and on the field, either through evaporation, through run-off or by percolation into the ground water.

Design can be viewed as the process of making decisions concerning the values of flow rate (Qo), length of channel (L), and time of cutoff (tco), prior to the onset of every irrigation season and during the project development phase. The available stream size, and the length and grade of the land units must be combined to achieve acceptable results without excessive labor, waste of water, erosion and inconvenience to other farming operations.

Since the performance of a surface irrigation system is dependent on three sets of variables; design, management, and field variables (system parameters), which are shown in the following functional relationship, it has of a paramount importance to discuss each one of them in detail.

\[ P = f ( I, S_o, n, Z_r, G, q_o, L, t_{co} ) \]

Where \( P \) = performance of surface irrigation

\( I \) = symbolizes the infiltration parameters

\( S_o \) = channel bed slope

\( n \) = hydraulic resistance

\( G \) = symbolizes geometry parameters

\( Z_r \) = required amount of application

\( q_o \) = unit flow rate at the head end of the channel

\( t_{co} \) = time of cut off

\( L \) = furrow length
A) Surface irrigation Design inputs (System Parameters and System Variables)

Generally there are two types of design data inputs in surface irrigation: field parameters and field decision variables. The designer can manipulate decision variables. They include flow rate, the field dimensions and cut-off time. On the other hand, however, the designer cannot influence Field parameters; they are measured or assumed properties of the given situation. They primarily consist of the soil infiltration characteristics, the flow resistance, the required net application depth, and the field slopes (for borders and furrows).

A description (explanation) of each design input parameter as related to its influence, dimensions and the procedures followed to determine each parameter would be presented in the subsequent sections.

**System Parameters**

1. **Required amount of application** ($d_n$): This parameter represents the amount of water that needs to be stored in the crop root zone reservoir during every irrigations, in order to sustain normal crop growth. The crop type, stage of growth, presence or absence of shallow water table, and limiting soil horizons (such as hard pans), among other things, determine the effective crop root depth. Soil type is the factor that determines how much water can be stored per unit depth of soil. These factors, along with the climatic conditions of an area should be considered to determine the required amount of application ($d_n$). For basins and borders the characteristics width is unit width, i.e. 1m, whereas for furrows it is the furrow spacing.

Note: $d_n$ is the same as MAD - **management allowable depletion** or **maximum allowable deficiency**. **MAD** is the soil moisture at which irrigations should be scheduled, and is determined as:

$$d_n = MAD = TAW \times D_r \times P, \quad TAW = (\text{Field capacity} - \text{Wilting point}) \times \text{Root zone depth}$$

![Components of soil water](image)

**Figure Components of soil water**
2. **Maximum allowable flow velocity** \( (V_{\text{max}}) \): This is used in estimating the non-erosive flow rate, \( Q_{\text{max}} \), which can be turned on into a furrow or a border or a basin without causing soil erosion. The value of \( V_{\text{max}} \) is generally depend on soil type, and may vary within the range of 8 m/min for erodible silt to 13 m/min for more stable clay and sandy soils.

3. **Manning’s roughness coefficient** (\( n \)): A parameter in Manning’s equation, known as the Manning’s \( n \), is used as a measure of the resistance effects that flow might encounter as it moves down the furrow, border or basin, which is in fact a representation, in lumped form, of the effect of the roughness of the physical boundaries of the flow and cultivation practices. Most of the time, the values for Manning’s \( n \) used for furrow, border and basin irrigation are based on the recommendation of the SCS and are given in the following table.

<table>
<thead>
<tr>
<th>Field condition</th>
<th>Manning’s ( n ) values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth bare soil surface non-cultivated, oil-mulched citrus</td>
<td>0.04</td>
</tr>
<tr>
<td>Small grain, drill rows parallel to direction of irrigation</td>
<td>0.10</td>
</tr>
<tr>
<td>Alfalfa, mint, broadcast small grain, and similar crops</td>
<td>0.15</td>
</tr>
<tr>
<td>Dense sod crops, small grain with drill rows across the border strip</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Source: USDA, 1979

4. **Channel bed slope** (\( S_{o} \)). The bed slope of a furrow or a border or a basin needs to be known in order to estimate maximum non-erosive flow rates as well as flow cross-sectional area or depth of flow at any given channel section using, say, Manning’s equation. Bed slope is the average slope in the direction of irrigation and is an easy parameter to measure. For borders and furrows bed slope should not be too high to cause scouring and must not too low as to result a very slow advance with the end outcome being inefficient irrigation. Usually the values recommended by USDA, which depend on soil (type and profile depth), crop combination (for borders) and size of individual furrows, are used. (See tables)

5. **Infiltration parameter** (\( I \)). Knowledge of the infiltration characteristics of the soil is critically important for evaluation, design or management of a surface irrigation system, without which it is very difficult to accurately judge system performance, application efficiency and uniformity. Therefore, infiltration parameter, \( k \), \( a \), and \( f_{o} \) should be determined prior to the actual design stage.

Generally infiltration rate and cumulative infiltration into an initially dry soil from a ponded water body can be represented as a sole function of time. Over the years several mathematical models have been developed which may broadly classified as:


   ii) Physically based models – (Green & Ampt, 1911)
iii) Empirical relationships - (Kostiakov 1932; Lewis 1933; Horton 1940; USDA 1979)

Owing to their simplicity and minimal data requirement commonly utilized equations in surface irrigation models are the Kostiakov- Lewis and modified Kostiakov- Lewis Equations.

**Kostiakov – Lewis Equation**

This was independently developed by Kostiakov and Lewis and has a form in which the infiltration rate is expressed as a single term monotonic decreasing power function of time.

The cumulative intake function (depth of infiltration) is given by

\[ Z = K t^a, \quad \text{differentiating over the time the infiltration rate (I) will be} \]

\[ I = a K t^{a-1} \]

Where \( Z \) = cumulative depth of infiltration, [L]

\( I \) = Rate of infiltration, [LT\(^{-1}\)]

\( K \) and \( a \) are infiltration constants obtained from curve fitting techniques.

The Kostiakov – Lewis equation, as per Philip (1957), describes both actual and theoretical infiltration very well on small to medium time scale. However, it has two major limitations.

- It can not be adjusted for field conditions known to have profound effects on infiltration such as Initial water content.
- After long periods of application it predicts an infiltration rate which approaches to zero, which is not always true.

**Modified form of Kostiakov – Lewis Equation:**

The cumulative intake is given by

\[ Z = K t^a + f_o t \]

, differentiating the preceding equation the corresponding rate of infiltration will be

\[ I = a K t^{a-1} + f_o \]

The new term, \( f_o \), represents the final, near constant, infiltration rate that would occur after long time of application. It is generally referred to as the basic infiltration (intake) rate.

**Soil Conservation Service method:**

This is an empirical infiltration function of wide importance from irrigation perspective developed by the United States Department of Agriculture soil conservation service (SCS, 1979).

The depth of infiltration (Z) is given by the following function.
\[ Z = at^b + c \]

Where \( Z \) = depth of infiltration

\[ t = \text{time of infiltration} \]

\[ a \text{ and } b = \text{constants given as function of the intake family} \]

\[ c = 0.275 \text{ for } Z \text{ in inches and equals to } 0.6985 \text{ for } Z \text{ in centimetres}. \]

The SCS has developed the concept of soil intake families, which classify soils in to broad categories according to their infiltration properties. The SCS soil intake families are identified by numerals ranging from 0.05 - 2.00 (sometimes 4).

**The intake family denoted by 2 for example represents a soil which absorbs 2 inches or 25.4mm of water over a unit surface area per hour after sufficiently long period of application.**

6. **Channel geometry:** The geometry of a channel cross-section has a significant effect on the surface hydraulics as well as infiltration. Generally, basins and borders can be considered as wide rectangular channels, where the depth of flow is by far less than their width. Furrows, on the other hand, can have parabolic, triangular or trapezoidal cross-sections. It is therefore important to take account of channel geometry in modeling of furrow irrigation processes.

For reasons of simplicity and practical considerations, such as accounting for irregularities in channel cross-sections, it is customary to assume that a power relationship holds between the following important channel geometry elements of a furrow.

\[ A = \sigma_1 y^{\alpha_2} \]

\[ W_p = \tau_1 y^{\alpha_2} \]

Where \( A \) = flow area

\[ W_p = \text{wetted perimeter} \]

\( \sigma_1, \sigma_2, \tau_1 \text{ and } \tau_2 \text{ are regression model parameters} \)

Similarly, furrow spacing depends upon the type of crop, equipment availability and soil type. Many crops are planted in single rows 75 to 105 cm apart.
Table 3: Area and hydraulic radius calculations for the three channel types

<table>
<thead>
<tr>
<th>Channel type</th>
<th>Area</th>
<th>Hydraulic radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trapezoidal</td>
<td>((b + my)y)</td>
<td>(\frac{(b + 2y)y}{b + 2y\sqrt{1 + m^2}})</td>
</tr>
<tr>
<td>Triangular</td>
<td>(my^2)</td>
<td>(my/(2\sqrt{1 + m^2}))</td>
</tr>
<tr>
<td>Semi-circular (parabolic)</td>
<td>(\pi r^2/2)</td>
<td>(r/2)</td>
</tr>
</tbody>
</table>

System Variables

1. **Channel length (L):** The length of a basin or border or a furrow should be determined considering the soil type, method of irrigation and from previous studies to estimate advance and recession over the length of the channel, the resulting distribution of infiltrated water, volume of runoff and the performance indices. There always exist a certain optimal channel length that would minimize irrigation water losses yet results in acceptable levels of adequacy and uniformity. If the above data is not available the following Tables can be used as guides.

Table 4: Typical border slopes, length and width for different soils

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Slope ranges (%)</th>
<th>Length range (M)</th>
<th>Width range(M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy to sandy loams</td>
<td>0.25-0.6</td>
<td>60-120</td>
<td>15-20</td>
</tr>
<tr>
<td>Medium loam</td>
<td>0.2-0.4</td>
<td>100-180</td>
<td>20-25</td>
</tr>
<tr>
<td>Clay to clay loam</td>
<td>0.05-0.2</td>
<td>150-300</td>
<td>25-35</td>
</tr>
</tbody>
</table>

Table 5: Maximum furrows lengths for given slopes, depth of water application and soils.

<table>
<thead>
<tr>
<th>Furrow Slope</th>
<th>75</th>
<th>150</th>
<th>225</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>50</th>
<th>75</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>340</td>
<td>440</td>
<td>470</td>
<td>180</td>
<td>340</td>
<td>440</td>
<td>90</td>
<td>120</td>
<td>190</td>
</tr>
<tr>
<td>Loam</td>
<td>400</td>
<td>500</td>
<td>620</td>
<td>280</td>
<td>400</td>
<td>500</td>
<td>150</td>
<td>220</td>
<td>280</td>
</tr>
<tr>
<td>Sands</td>
<td>400</td>
<td>500</td>
<td>560</td>
<td>280</td>
<td>370</td>
<td>470</td>
<td>120</td>
<td>190</td>
<td>250</td>
</tr>
</tbody>
</table>

2. **Unit inlet flow rate (Qo):** This is the discharge diverted into a furrow, or a unit width border or a basin. Inlet flow rate is one of the key variables in influencing the outcome of an irrigation event; it affects, the rate of advance to a significant degree and also recession to a lesser but appreciable extent. Thereby having a significant effect on uniformity, efficiency and adequacy of irrigation, it should not be too high as to cause scouring and should not be too small as otherwise the water will not advance to the down stream end.
3. Cutoff time (tco): Cut off time is the time at which the supply is turned off, measured from the onset of irrigation. The ideal time of cutoff occurs when the infiltrated depth in the least-watered portion of the field is equal to the irrigation requirement. The most important effect of cutoff is reflected on the amount of losses, deep percolation and surface runoff, and hence efficiency and adequacy of irrigation. In general for any given factor level of combination the selection of an appropriate value of tco is made on the basis of the target application depth and acceptable level of deficit.

B) Surface irrigation system performance

Ideally the best surface irrigation scenario (event) is one that can apply the right amount of water over the entire subject area and without loss, a situation which requires that equal amount of water be applied over the entire reach of the channel. In practice however there exist no surface irrigation system or operation scenarios that can apply water without loss and with perfect uniformity. In any case making uneven application of water over the length of run of a channel is unavoidable. The inevitable consequence of this is that in order to apply a certain target amount of water at a point, say down stream end of the subject area, a larger amount must be applied at another point. What all these indicate is that in real life systems uneven and excess application of irrigation water are the “twins facts of life’ that engineers and irrigators ought to live with. We cannot do without them but we ought to strive to minimize them. That is what system design and management is all about. The merit of an irrigation scenario (event) is judged in terms of indices that “measure how close an irrigation scenario is to the ideal one”. These indices are collectively referred to as performance indices. The performance of a surface irrigation event can be evaluated from three distinct but complementary perspectives.

1) Excess application of irrigation water, though unavoidable in real life situation must be minimized (minimum loss). Application efficiency (Ea) is the index which is used as a measure of how effective irrigation is in minimizing unavoidable losses.

2) Adequacy of irrigation, evaluated in terms of a perceived requirement is necessary to sustain normal crop growth and result in satisfactory yield. Water storage efficiency (Es) uses how close the applied amount is to the perceived requirement (right amount).

3) Uniform (even) application of irrigated water over the entire subject area not only enhances productive use of available water by spreading deficit, if any, over the subject area but also helps minimize losses. Distribution uniformity (DU) and Christiansen’s uniformity coefficient (UC) are the most commonly used indices in surface irrigation application. Moreover, deep percolation and run-off losses are vital in constraining as well as guiding operational decision making processes. It nonetheless is appropriate to threat them as performance term as per se.

Irrigation uniformity

Uniformity of infiltration under surface irrigation depends on the spatial and temporal variability of surface and sub-surface hydraulic characteristics such as field slope, furrow geometry, surface roughness, field length, flow rate and soil pore size distribution.
Two parameters are used to evaluate distribution uniformity.

The first parameter is **distribution uniformity coefficient** DU, and is defined as the ratio of the minimum infiltrated amount expressed as percentage of the average infiltrated amount over the subject area. A general expression for DU is:

$$DU = \frac{Z_{\text{min}}}{Z_{\text{av}}} \times 100$$

Where

- $Z_{\text{min}}$ = minimum infiltrated amount over the length of the run of the subject area (m$^3$.m$^{-1}$).
- $Z_{\text{av}}$ = average infiltrated amount over the length of the run of the subject area (m$^3$.m$^{-1}$) and

The second parameter is **Christiansen `s uniformity coefficient**, (UCC), defined as the ratio of the difference between the average amount applied and the average deviation from the average amount applied to the average amount applied.

It is given by the equation:

$$UCC = \left[ 1 - \frac{\sum_{i=1}^{N} |Z_i - Z_{\text{av}}|}{Z_{\text{av}} N} \right] \times 100$$

Where $Z_i$ = infiltrated amount at point $i$ (m$^3$.m$^{-1}$)

- $N$ = number of points used in the computation of UCC

### 2.4.1. Furrow irrigation System design

**Non erosive stream size**

To maintain proper furrow shape and reduce sediment loss from the head of the field and deposition at the tail of the field or adjacent water way, it is desirable to operate the furrow at a velocity that is non erosive.

The empirical relation developed by USDA-SCS for the maximum non-erosive stream size is

$$Q_{\text{max}} = \frac{C}{S} \quad \text{.................................................................(1)}$$

Where $S$ = ground slope down the furrow in %

- $C$ = empirical constant (= 0.6 $\ell/s$)

- This relationship doesn’t account for soil type and therefore limited in accuracy
**Table 6**: Relation of maximum non erosive flow rates to critical slopes of furrows (after Booher, 1974)

<table>
<thead>
<tr>
<th>Furrow slope S (%)</th>
<th>Maximum flow rate, ( Q_{max} \cdot \frac{ℓ}{s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>6.0</td>
</tr>
<tr>
<td>0.3</td>
<td>2.0</td>
</tr>
<tr>
<td>0.5</td>
<td>1.2</td>
</tr>
<tr>
<td>2.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Table 7** intake family and advance coefficients for depth of infiltration in mm, time in minutes and length in meters.

<table>
<thead>
<tr>
<th>Intake family</th>
<th>Soil type</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>f</th>
<th>g</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>Clay</td>
<td>0.5334</td>
<td>0.618</td>
<td>7.0</td>
<td>7.16</td>
<td>1.088*10^-4</td>
</tr>
<tr>
<td>0.10</td>
<td>Clay</td>
<td>0.6198</td>
<td>0.661</td>
<td>7.0</td>
<td>7.25</td>
<td>1.25*10^-4</td>
</tr>
<tr>
<td>0.15</td>
<td>Light clay</td>
<td>0.7110</td>
<td>0.683</td>
<td>7.0</td>
<td>7.34</td>
<td>1.414*10^-4</td>
</tr>
<tr>
<td>0.20</td>
<td>Clay loam</td>
<td>0.7772</td>
<td>0.699</td>
<td>7.0</td>
<td>7.43</td>
<td>1.578*10^-4</td>
</tr>
<tr>
<td>0.25</td>
<td>Clay loam</td>
<td>0.8534</td>
<td>0.711</td>
<td>7.0</td>
<td>7.52</td>
<td>1.741*10^-4</td>
</tr>
<tr>
<td>0.30</td>
<td>Clay loam</td>
<td>0.9246</td>
<td>0.720</td>
<td>7.0</td>
<td>7.61</td>
<td>1.904*10^-4</td>
</tr>
<tr>
<td>0.35</td>
<td>Silty</td>
<td>0.9957</td>
<td>0.729</td>
<td>7.0</td>
<td>7.70</td>
<td>2.067*10^-4</td>
</tr>
<tr>
<td>0.40</td>
<td>Silty</td>
<td>1.064</td>
<td>0.736</td>
<td>7.0</td>
<td>7.79</td>
<td>2.230*10^-4</td>
</tr>
<tr>
<td>0.45</td>
<td>Silty loam</td>
<td>1.130</td>
<td>0.742</td>
<td>7.0</td>
<td>7.88</td>
<td>2.393*10^-4</td>
</tr>
<tr>
<td>0.50</td>
<td>Silty loam</td>
<td>1.196</td>
<td>0.748</td>
<td>7.0</td>
<td>7.97</td>
<td>2.556*10^-4</td>
</tr>
<tr>
<td>0.60</td>
<td>Silty loam</td>
<td>1.321</td>
<td>0.757</td>
<td>7.0</td>
<td>8.15</td>
<td>2.883*10^-4</td>
</tr>
<tr>
<td>0.70</td>
<td>Silty loam</td>
<td>1.443</td>
<td>0.766</td>
<td>7.0</td>
<td>8.33</td>
<td>3.209*10^-4</td>
</tr>
<tr>
<td>0.80</td>
<td>Sandy loam</td>
<td>1.560</td>
<td>0.773</td>
<td>7.0</td>
<td>8.50</td>
<td>3.535*10^-4</td>
</tr>
<tr>
<td>0.90</td>
<td>Sandy loam</td>
<td>1.674</td>
<td>0.779</td>
<td>7.0</td>
<td>8.68</td>
<td>3.862*10^-4</td>
</tr>
<tr>
<td>1.00</td>
<td>Sandy loam</td>
<td>1.786</td>
<td>0.785</td>
<td>7.0</td>
<td>8.86</td>
<td>4.188*10^-4</td>
</tr>
<tr>
<td>1.50</td>
<td>Sandy</td>
<td>2.284</td>
<td>0.799</td>
<td>7.0</td>
<td>9.76</td>
<td>5.819*10^-4</td>
</tr>
<tr>
<td>2.00</td>
<td>Sandy</td>
<td>2.753</td>
<td>0.808</td>
<td>7.0</td>
<td>10.65</td>
<td>7.451*10^-4</td>
</tr>
</tbody>
</table>

The average intake over the length of the furrow is given by

\[
I = \frac{1}{LP} (V_{in} - V_{out} - V_s) \tag{2}
\]

Where \( I \) = equivalent depth infiltrated over wetted surface area of field, mm
\( L \) = distance between inflow and outflow measurements, m
\( P \) = adjusted wetted perimeter, m
\( V \) = volume of water (inflow, outflow, storage) in liter.

The adjusted wetted perimeter in given by the following equation

\[
P = 0.265 \left( \frac{Q_n}{S^{0.5}} \right)^{0.425} + 0.227 \tag{3}
\]

Where \( Q \) = volumetric inflow rate, \( \frac{ℓ}{s} \)
\( N \) = Manning’s roughness coefficient
\( S \) = furrow slope or hydraulic gradient, \( \frac{m}{m} \)
In most cases, after the flow has stabilized and gets uniform, the hydraulic gradient is equal to the furrow slope. A roughness coefficient of 0.04 is normally used for design of furrow irrigation system.

The volume of channel storage is given by
\[
V_s = \frac{L}{0.305} \left[ 2.947 \left( \frac{Qn}{S^{0.5}} \right)^{0.735} - 0.0217 \right] \quad \text{(4)}
\]

The required depth of infiltration for a furrow system must be expressed as an equivalent depth over the total field area. Infiltration depth is given by:
\[
I = \left[ at^b + C \right] \frac{P}{W} \quad \text{-----------------------------------------------(5)}
\]

Where \(a, b, c\) are intake family coefficients

\(t\) = time, min
\(W\) = furrow spacing, m
\(P\) = adjusted wetted perimeter, m

The advance time for stream of water moving down the furrow is given by
\[
T_t = \frac{X}{f} \exp\left[ \frac{gx}{QS^{0.5}} \right] \quad \text{-----------------------------------------------(6)}
\]

Where \(T_t\) = advance time, min
\(X\) = distance down the furrow, m
\(f\) = advance coefficient (Table 7)
\(g\) = advance coefficient
\(Q\) = volumetric inflow rate, \(\ell/s\)
\(S\) = furrow slope, \(m/m\)

The infiltration opportunity time is equal to the time of water application minus the advance time plus the recession time.
\[
T_o = T_{co} - T_t + T_r \quad \text{min} \quad \text{-----------------------------------------------(7)}
\]

The cut-off time, \(T_{co}\), reflects an irrigation management decision made by the farmer and designer. It should be an adequate length of time to infiltrate a satisfactory depth of water over the length of the furrow without causing excessive deep percolation. \(T_{co}\) is normally set equal to the time to advance to the end of the furrow plus the required net infiltration time less recession time. Letting in equal the desired net depth of infiltration, the net infiltration time is determined by
\[
T_n = \left[ \frac{i_n \left( \frac{w}{P} - C \right)}{a} \right]^{1/b} \quad \text{-----------------------------------------------(8)}
\]

The recession time is assumed zero for open-ended gradient furrows (i.e. for furrows whose slope is not equal to zero) without loss of accuracy.

For gradient furrows, \(T_o = T_{co} - T_t \quad \text{-----------------------------------------------(9)}\)

but
\[
T_{co} = T_t + T_n
\]

Where \(T_t\) = advance time required to reach end of the field at distance \(L\), min.
Let \( \beta = \frac{g x}{Q S^{0.5}} \)

The average infiltration opportunity time over distance \( x \) down the furrow is given by:

\[
T_{o-x} = T_{co} - \frac{0.0929}{f(x) \left[ \frac{0.305 \beta}{x} \right]^2} \left[ (\beta - 1) \exp(\beta) + 1 \right]
\]  

(10)

The average infiltration time for the full furrow length, \( T_{o-L} \), is obtained by substituting \( L \), in to \( eg^n \) (10) for \( x \). the average depth of infiltration for the entire furrow length, \( i_{avg} \), is therefore determined by substituting \( T_{o-L} \) in to \( eg^n \) (5) for \( t \).

The gross depth of water application, \( i_g \), is defined as the required net depth of irrigation, \( i_n \), divided by the product of the application and distribution pattern efficiencies.

\[
i_g = \frac{i_n}{E_A E_d}
\]  

(11)

If evaporation is neglected, \( E_a \) is assumed to be equal to 100%

\[
i_g = \frac{i_n}{E_d}
\]  

(12)

The equivalent gross depth of application as a function of inflow rate and field geometry, is

\[
i_g = \frac{60(Q/T_{co})}{W L}
\]  

(13)

\( i_g \) = gross depth of application in mm  
\( Q = \) inflow rate, \( \ell/s \)  
\( W = \) furrow spacing, m

The equivalent depth of deep percolation, \( d_{dp} \)

\[
D_{dp} = i_{avg} - i_n
\]  

(14)

**Example:** Given the following information,

Intake family, IF = 0.3  
Furrow length, \( L = 275 \) m  
Furrow slope, \( s = 0.004 \) m/m  
Roughness coefficient, \( n = 0.04 \)  
Net irrigation depth, \( i_n = 75 \) mm  
Inflow rate, \( Q = 0.6 \ell/s \)

Compute the desired time to cut – off, \( T_{co} \), the equivalent depths of surface run off and deep percolation, \( d_{ro}, d_{dp}, \) and the distribution pattern efficiency. 

**Sol**:

For Intake family IF = 0.3,  
\( a = 0.9246 \),  \( b = -0.720 \),  \( c = 7.0 \),  \( g = 7.61 \)

\[ f = 1.904 \times 10^{-4} \]

- Advance time \( T_t \)
DESIGN OF SURFACE IRRIGATION, LECTURE SUPPORTING MATERIALS

\[ T_1 = \frac{x}{f} \exp \left[ \frac{gX}{QS^{0.5}} \right] = 275m \frac{0.6}{0.6} \exp \left[ \frac{(1.904 \times 10^{-4}) & 275}{0.6(0.004)^{0.5}} \right] = 144 \text{ min} \]

- Adjusted wetted perimeter, P

\[ P = 0.265 \left( \frac{Qn}{S^{0.5}} \right)^{0.425} + 0.227 = 0.265 \left( \frac{0.6 \times 0.04}{(0.004)^{0.5}} \right)^{0.423} + 0.227 = 0.40m \]

- Net Infiltration time, \( T_n \)

\[ T_n = \left[ \frac{i_n \left( \frac{w}{p} \right) - C}{a} \right]^{\frac{V_b}{s}} = \left[ \frac{75mm \left( \frac{0.75m}{0.4} \right) - 7.0}{0.925} \right]^{\frac{V}{0.720}} = 999 \text{ min} \]

- Design cut-off time, \( T_{co} \)

\[ T_{co} = T_1 + T_n = 144 + 999 = 1143 \text{ min}. \]

- Gross application depth, \( I_g \)

\[ I_g = \frac{60(Q)(T_{co})}{WL} = \frac{60(0.6)}{0.75m \times 275m} = 200mm \]

- Average infiltration Time, \( T_{O-L} \)

\[ T_{O-L} = T_{co} - \frac{0.0929}{f(x)[0.305\beta^2]} \left[ (\beta - 1) \exp(\beta) + 1 \right] \quad \text{where} \quad \beta = \frac{gX}{QS^{0.5}} \]

Substituting for all the variables

\[ T_{O-L} = 1143 - 47.6 = 1095 \text{ min}. \]

- Average infiltration, \( i_{avg} \)

\[ i_{avg} = (aT_{O-L} + c) \frac{P}{W} = [(0.925)(1095) + 7.0] \frac{0.40}{0.75} = 80mm \]

- Surface runoff depth, \( d_{ro} \)

\[ d_{ro} = I_g - i_{avg} = 200mm - 80mm = 120mm \]

- Deep percolation depth, \( d_{dp} \)

\[ d_{dp} = i_{avg} - i_n = 80mm - 75mm = 5mm \]

- Distribution pattern efficiency, \( e_d \)

\[ e_d = \frac{i_n}{i_g} \times 100 = \frac{75mm}{200mm} \times 100\% = 37.5\% \]

The following modifications are necessary to solve the hydraulic equation for the cut – back conditions. The adjusted wetted perimeter under the cut – back conditions is computed by substituting \( Q_2 \) in to equation (3). The required net infiltration time at length \( L \) is solved for by substituting \( P_2 \) in to equation (6). The average opportunity
time for infiltration during the advance period is given by the absolute value of the second term on the right hand side of equation (10) with X set equal to L.

\[ T_{avg} = \frac{0.0929}{f(L)} \left( \frac{0.305 \beta}{L} \right)^2 \left[ (\beta - 1) \exp(\beta) + 1 \right] \]

The average infiltration under the cut – back condition is

\[ I_{avg} = \left[ a(T_{co} - T_{avg})^b + C \right] \frac{P_2}{w} + \left[ a(T_{avg})^b + c \right] \frac{P_1 - P_2}{w} \]

The gross depth of application is given by

\[ I_g = \frac{60}{WL} [Q_1(T_i) + Q_2(T_n)] \]

**Example:** Given the same condition as example problem above, compute the same information required for that problem, if a cut back system is used and Q is reduced by one-half.

**Sol**

- Time of cut-back, \( T_{cb} \), is the time of advance at full flow, \( T_1 \), and is equal to that calculated in the previous example.

\[ T_{cb} = T_1 = 144 \text{ min.} \]

- Adjusted wetted perimeter during advance is is \( P \) as calculated in previous example.

\[ P = 0.40 \text{m} \]

- Adjusted wetted perimeter during reduced flow is calculated with flow \( Q_2 \)

\[ P_2 = 0.265 \left( \frac{Q_2H}{S^{0.5}} \right)^{0.425} + 0.227 = 0.265 \left( \frac{0.3 \times 0.04}{0.004^{0.5}} \right)^{0.425} + 0.227 = 0.36 \text{m} \]

- Net application time is the time water must remain on the surface at the end of the field and equal to \( T_n \) under reduced flow condition.

\[ T_n = \left[ \frac{i_n \left( \frac{w}{P_2} \right) - C}{a} \right]^{\frac{1}{b}} = \left[ \frac{75 \text{mm} \left( \frac{0.75 \text{m}}{0.36} \right) - 7.0}{0.925} \right]^{\frac{1}{0.720}} = 1165 \text{ min} \]

- Time of cut-off is the sum of \( T_1 \) and \( T_n \)

\[ T_{co} = 144 + 1165 = 1309 \text{ min.} \]

- Average infiltration during the advance period is the absolute value of the second term of equation (10) and was calculated in the previous example as part of \( T_{O-L} \)

\[ T_{avg} = 47.6 \text{ min.} \]

- Average infiltration, \( i_{avg} \)

\[ I_{avg} = \left[ a(T_{co} - T_{avg})^b + C \right] \frac{P_2}{w} + \left[ a(T_{avg})^b + c \right] \frac{P_1 - P_2}{w} \]
\[ I_{\text{avg}} = \left[ 0.925(1309 - 47.6)^{0.720} + 7.0 \right]^{0.36} + \left[ 0.925(47.6)^{0.720} + 7.0 \right]^{0.40 - 0.36} \]
\[ = 79 + 1.2 = 80 \text{mm} \]

- Gross application depth

\[ I_g = \frac{60}{0.75 \times 275} [0.6(144) + 0.3(1165)] = 127 \text{ mm} \]

- Surface runoff depth, \( d_{ro} \)

\[ d_{ro} = i_g - i_{\text{avg}} = 127 \text{ mm} - 80 \text{ mm} = 47 \text{ mm} \]

- Deep percolation depth, \( d_{dp} \)

\[ d_{dp} = i_{\text{avg}} - i_n = 80 \text{ mm} - 75 \text{ mm} = 5 \text{ mm} \]

- Distribution pattern efficiency, \( e_d \)

\[ e_d = \frac{i_n \times 100}{i_g} = \frac{75 \text{ mm}}{127 \text{ mm}} \times 100\% = 59\% \]

### 2.4.2. Level Basin System Design

Fields to be irrigated by a level basin system are divided into level rectangles of limited extent by ridges of adequate height to retain the depth of flow. The entire field is flooded and the water is allowed to infiltrate into the root zone after ponding on the soil surface. Level basin systems are designed on the basis of water application rate, soil intake family, and field dimensions.

As with furrow systems, empirical relations have been developed for the design of level basin systems based on reasonably successful designs in field situations. These relationships are a compromise between available stream sizes, soil intake family, basin size and irrigation efficiency.

**Table 8: suggested basin area for different soil types and rates of water flow (taken from Booher, 1974)**

<table>
<thead>
<tr>
<th>Flow rate l/s</th>
<th>Area in hectares</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sand</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>30</td>
<td>108 0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>60</td>
<td>216 0.04</td>
<td>0.12</td>
</tr>
<tr>
<td>90</td>
<td>324 0.06</td>
<td>0.18</td>
</tr>
<tr>
<td>120</td>
<td>432 0.08</td>
<td>0.24</td>
</tr>
<tr>
<td>150</td>
<td>540 0.10</td>
<td>0.30</td>
</tr>
<tr>
<td>180</td>
<td>648 0.12</td>
<td>0.36</td>
</tr>
<tr>
<td>210</td>
<td>756 0.14</td>
<td>0.42</td>
</tr>
<tr>
<td>240</td>
<td>864 0.16</td>
<td>0.48</td>
</tr>
<tr>
<td>270</td>
<td>972 0.18</td>
<td>0.54</td>
</tr>
<tr>
<td>300</td>
<td>1080 0.20</td>
<td>0.60</td>
</tr>
</tbody>
</table>
Hydraulic relationships

The hydraulic relationships described in this section are based on design procedures developed by the soil conservation service and will use the intake family concept the equations in this section can be derived by application of the continuity, infiltration and Manning’s equations with limited depth of flow.

The net time of infiltration, $T_n$, in a level basin system is computed using equation

$$T_n = \left[ \frac{i_n - C}{a} \right]^{1/6} \quad \text{.......................... (17)}$$

The required advance time, $T_t$, is determined by multiplying the net infiltration time by the fractional advance ratio, $\frac{T_t}{T_n}$, which is a function of distribution pattern efficiency.

Table 9 Ratio of $T_t$ to $T_n$ for various distribution efficiency values.

<table>
<thead>
<tr>
<th>Distribution pattern Efficiency (Ed) %</th>
<th>Ratio $T_t$ to $T_n$ ($\frac{T_t}{T_n}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>0.16</td>
</tr>
<tr>
<td>90</td>
<td>0.28</td>
</tr>
<tr>
<td>85</td>
<td>0.40</td>
</tr>
<tr>
<td>80</td>
<td>0.58</td>
</tr>
<tr>
<td>75</td>
<td>0.80</td>
</tr>
<tr>
<td>70</td>
<td>1.08</td>
</tr>
<tr>
<td>65</td>
<td>1.45</td>
</tr>
<tr>
<td>60</td>
<td>1.90</td>
</tr>
<tr>
<td>55</td>
<td>2.45</td>
</tr>
<tr>
<td>50</td>
<td>3.20</td>
</tr>
</tbody>
</table>

$$Ed = 105.81 - 32.676 \left( \frac{T_t}{T_n} \right)^{0.5} \quad \text{...........(18)}$$

Table 10: Values of the roughness coefficients used in level basin and graded border systems.

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth, bare soil surfaces non cultivated, citrus</td>
<td>0.04</td>
</tr>
<tr>
<td>Small grain, rows parallel to border strip</td>
<td>0.10</td>
</tr>
<tr>
<td>Alfalfa, broad east small grains, and similar crops</td>
<td>0.15</td>
</tr>
<tr>
<td>Dense sod crops, small grains with rows across the border strip</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The relationship between the advance time, basin length, and inflow rate will apply the unit inflow rate concept.

$$L = \frac{6 \times 10^4 (Q_a)T_t}{a(T_t)^b + c + 1798n^{7/8}(Q_a)^{9/16}(T_t)^{3/16}} \quad \text{.......................... (19)}$$
Where \( Q_u = \frac{Q}{W}, \ W = \text{basin width} \) (20)

The time to cut-off, \( T_{co} \), is the time required to put the gross depth of irrigation, \( i_g \) on to the basin is given by

\[
T_{co} = \frac{i_n L}{600Q_u e_d} \quad \text{.................. (21)}
\]

Where: \( T_{co} = \text{time to cut-off, min} \)  
\( i_n = \text{net depth of irrigation, mm} \)

The maximum depth of flow in the basin, \( d_{max} \), is an important parameter in basin design in that it governs the minimum ridge height. The ridge height should be equal to 1.25 times the maximum depth of flow and the ridge should have a maximum side slope ratio of 2.5:1

\[
d_{max} = 2250 n^{3/8} Q_u^{9/16} T_{co}^{3/16}
\]

Where \( d_{max} = \text{maximum flow depth, mm} \)

Example: Given the following information
- Intake family \( I_f = 0.5 \)
- Targeted distribution pattern efficiency \( e_d = 80\% \)
- Unit flow rate \( Q_u = 0.005 \text{ m}^2/\text{s} \)
- Net irrigation depth \( i_n = 100\text{mm} \)
- Roughness coefficient \( n = 0.15 \)

Assuming 100 percent application efficiency, compute the net infiltration time, basin length, time – to – cut off, and maximum depth of flow.

Sol
2.4.3. Graded Border System Design

Graded border systems are similar in concept to level basin systems except that there is a slope down the border and there may be limited cross slope. Graded border systems may be more conveniently applied to soils of limited depth than level basin systems because of reduced leveling requirements.

Graded border systems are most applicable to soils with moderately low to moderately high in take rates. This method is best suited to lands with slopes less than 0.5%. It can be used on lands of slopes up to 2% for non grassy crops and up to approximately 4% for sod crops.

Hydraulic Relationships

The hydraulic relationships applied are complicated Relative to level basins in that the water applied is continuously moving down slope. The hydraulic relationships are derived by consideration of the continuity relationship, manning equation and the assumption that the amount of water infiltrated in to the soil may be approximated by the volume of a section with a triangular cross-sectional shape as the recession curve moves down the field.

Graded border systems are designed on the principle that any point in the field should have water applied to it for a time equal to that required to infiltrate the net depth of irrigation. Recession lag time: The time between cut-off of water at the head of the filed and the disappearance of water at the head of the field.

Time to cut-off, $T_{cco} = T_n - T_{rl}$

The term high gradient borders is used to denote borders with a surface slope greater then approximately 0.004m/m. In such borders, the water surface slope is assumed equal to the field slope and the normal flow depth, that is, the depth of flow under conditions of uniform flow is assumed equal to the depth of flow at the head of the border. Under such conditions, the recession lag time is given by:

$$T_{rl} = \frac{Q_u^{0.2} n^{1.2}}{120S^{1.6}}$$

Where $T_{rl}$ = recession lag time, min
$Q_u$ = unit flow rate, m2/s
$n$ = Manning’s roughness coefficient
$S$ = surface slope, m/m

- For low gradient borders with surface slopes less than 0.004m/m

$$T_{rl} = \frac{Q_u^{0.2} n^{1.2}}{120 \left[ S + \frac{0.0094nQ_u^{0.175}}{T_u^{0.88}S^{0.5}} \right]^{1.6}}$$

Where $T_n$ = net infiltration time, min.

- The inflow rate per unit width of border strip is given by
\[ Q_u = \frac{0.00167 i_n L}{(T_n - T_r)_{ed}} \]

where:

- \( i_n \) = net depth of irrigation
- \( L \) = border length, m
- \( e_d \) = Distribution efficiency, %

The maximum depth of flow in the In the border strip is determined by the border ridge height. The border ridge height is normally established at 1.25 times the maximum flow depth. Maximum flow depths of less than 150 mm are generally acceptable. In erosion resistant soil, flow depths in the range of 200mm may be acceptable.

Normal depth for uniform flow, (mm)

\[
d_n = \frac{1000 Q_u^{0.6} n^{0.6}}{S^{0.3}} \quad \text{for high gradient border}
\]

\[
d_n = 2454 (T_r)^{0.1875} Q_u^{0.5625} n^{0.1875} \quad \text{for low gradient border}
\]

The maximum flow rate criterion has been established to have a non – erosive stream size.

\[
Q_{u\text{max}} = \frac{1.765 \times 10^{-4}}{S^{0.75}} \quad \text{For alfalfa and small grains}
\]

\[
Q_{u\text{max}} = \frac{3.53 \times 10^{-4}}{S^{0.75}} \quad \text{for well established dense sod crops, pasture & grasses}
\]

A minimum depth of flow criterion is required to ensure that the water stream is large enough to spread over the entire border.

\[
Q_{u\text{min}} = \frac{5.95 \times 10^{-6} LS^{0.5}}{n}
\]

The theoretical relationship for maximum slope is given by

\[
S_{\text{max}} = \left[ \frac{n}{0.0117 e_d} \cdot \frac{i_n}{T_n - T_r} \right]^2
\]

The theoretical relationship for maximum length is given by

\[
L_{\text{max}} = \frac{Q_{u\text{max}} e_d (T_n - T_r)}{0.00167 i_n}, \quad e_d \text{ in %}
\]