Improving Performance of Surface Irrigation System by Designing Pipes for Water Conveyance and On-Farm Distribution

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1 Introduction

Egypt is an arid country with a high rate of population growth and escalating living standards. The natural and geographical conditions of Egypt are not auspicious in terms of freshwater resources availability [1]. Egypt faces significant challenges due to its limited water resources by enforcement policies to improve the performance of existing irrigation systems and its development. However, agriculture is the major consumer of water. Following are the measures applied to agriculture among a complete package of water saving techniques, and one of these techniques is the use of modern irrigation systems in newly reclaimed land [2]. The improvement of irrigation systems is one of the most essential attempts in Egypt to implement more efficient irrigation technologies. This chapter presents an overview of the hydraulics of surface irrigation system, installing new or improved systems, engineering indicators of performance assessment, on-farm water distribution by the applied irrigation system, and example of practices problems by case studies at different sites. Over the long term, irrigation must be adequate but not excessive to prevent harmful accumulation of salt in the root zone and to prevent a high water table that may contribute to salt accumulation at the soil surface [3].

Infiltrated depths of water must be relatively uniform to meet the crop's need and leach salt adequately, without excessive surface runoff or deep percolation. To meet such depth and uniformity requirements, irrigation systems must be suited to the site conditions, well-designed, and well-managed [4].

The chapter provides an in-depth comparison of design restrictions, characterization, and approaches to each situation. As such, after reading this chapter, an interested reader should be able to identify both successful and problematic approaches used to cope with various aspects of the surface irrigation. Such an outcome should

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prove useful to researchers, practitioners, water managers, and policymakers who are looking to improve their baseline understanding of surface irrigation development from different disciplines and levels of management.

By evaluating the level of the existing irrigation system, it possible to understand the farmer's practices in their traditional farms and enhancement it by improving the common irrigation system.

Thorough understanding of the effects of surface irrigation design quality is needed. This chapter summarizes the previous work on the effects of irrigation water distribution on water consumed, soil, and crop production.

2 Primary Theories of Water Flow by Pipes

By gravity that the water stored in the tank goes down by its own weight inside the pipes and run out. The water pressure is the force which water exerts in the walls of the container it is contained (pipe's walls, reservoir's wall).

The pressure in a considered point corresponds (or its equivalent) to the weight of the water column above this point. Knowing that the density of water is 1 g cm^{-3}, we can easily calculate the water column weight above a given point:

$$\text{Water column weight} = \text{water density} \times \text{water column height} = 1\ \text{g cm}^{-3}$$

2.1 Water Pressure—Static and Dynamic Head

- Static water pressure:

The pressure exerted by static water depends only upon the depth of the water, the density of the water, and the acceleration of gravity. The pressure in static water arises from the weight of the water and is given by the expression:

$$P_{\text{static water}} = \rho g h \tag{1}$$

where

$\rho = m/V$ water density
g acceleration of gravity
h depth of water.

The pressure from the weight of a column of liquid of area A and height h is shown in Fig. 1.

Because of the ease of visualizing a column height of a known liquid, it has become common practice to state all kinds of pressures in column height units, like

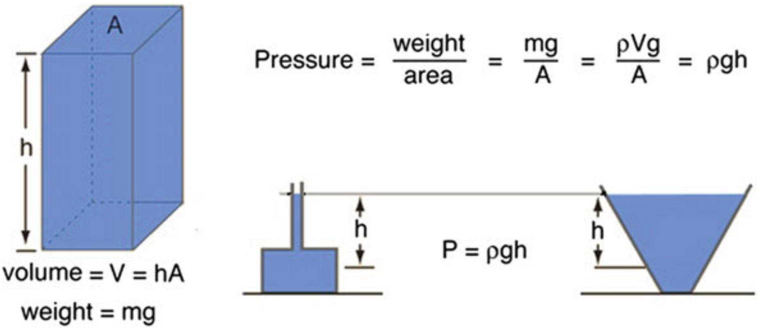

Fig. 1 Schematic form of static pressure concept

mmHg or cm H_2O, etc. Pressures are often measured by manometers in terms of a liquid column height and do not depend on the shape, total mass, or surface area of the liquid.

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- **Hydraulic and energy grade line for pipe flow**

Hydraulic calculations are required to design irrigation pipes. A hydraulic grade line analysis is required for all designs to ensure that water flows through the pipes in the manner intended.

The total energy of flow in a pipe section (with respect to a reference datum) is the sum of the elevation of the pipe center (elevation head). The pressure exerted by the water in the pipe expressed or shown by the velocity head and the height of a column of water (pressure head, or piezometric head, if a piezometer is provided in the pipe).

The total energy of flowing water, when represented in figure, is termed as energy grade line or energy gradient. The pressure of water in the pipe represented by elevation when drawn in line is termed as hydraulic grade line or hydraulic gradient as shown in Fig. 2.

- **Types of flow in pipe—Reynolds number**

The flow of water in pipes is of two types: laminar and turbulent. In laminar flow, the fluid moves in layers called luminous. In turbulent flow, secondary random motions are superimposed on the principal flow, and mixing occurs between adjacent sectors. In 1883, Reynolds introduced a dimensionless parameter (which has since been known as Reynolds number) that gives a quantitative indication of the laminar to turbulent transition. Reynolds number R_N according to [5] is

$$R_N = \frac{\rho V d}{\mu} \tag{2}$$

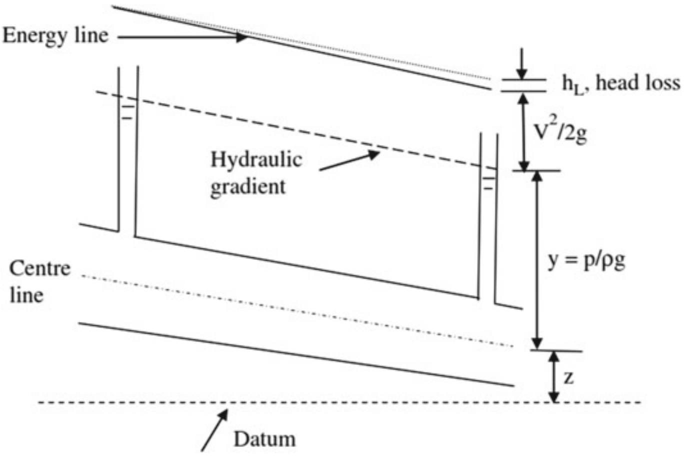

Fig. 2 Schematic of hydraulic and energy line in pipe flow

where

ρ density of fluid (kg m^{-3})
V mean fluid velocity (m s^{-1})
d diameter of the pipe (m)
μ coefficient of viscosity of the fluid (kg m^{-1} s^{-1}).

Generally, a flow is laminar if $R_N \leq 2100$. A transition between laminar and turbulent flow occurs for R_N between 2100 and 4000 (transition flow). Above 4000, the flow is turbulent. At turbulence range, the flow becomes unstable, and there is increased mixing that result in viscous losses which are generally much higher than those of laminar flow.

The Reynolds number can be considered in another way, as

$$R_N = \frac{\text{Inertia forces}}{\text{Viscous forces}} \tag{3}$$

The inertia forces represent the fluid's natural resistance to acceleration. The viscous forces arise because of the internal friction of the fluid. In a low Reynolds number flow, the inertia forces are small and negligible compared to the viscous forces, whereas in a high Reynolds number flow, the viscous forces are small compared to the inertia forces.

- **Velocity Profile of Pipe Flow**

Typical velocity profile of a pipe flow is shown in Fig. 3. The velocity is zero at the surface, increases after that, and reaches its maximum at the center of the pipe.

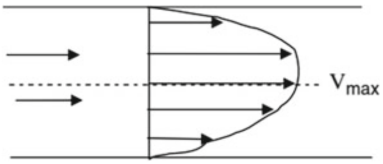

Fig. 3 Diagram showing velocity distribution in pipe flow

2.2 Calculation of Head Losses in Pipe Flow

- **Causes and components of head loss**

When fluid flows through the pipe, the internal roughness of the pipe wall can create local eddy currents vicinity to the surface, thus adding a resistance to the flow of the pipe. Pipes with smooth walls have only a small resistance to flow (frictional resistance). Smooth glass, copper, and polyethylene have small frictional resistance, whereas cast iron, concrete, steel pipe, etc., create larger eddy currents and effect on frictional resistance.

- **Importance of designing pipe sizes for irrigation water flow**

Determination of head loss (meaning loss of energy) in the pipe is necessary because the pump and motor (power) combination should be matched to flow and pressure requirement [6]. Oversizing makes for inefficiencies that waste energy and cost money.

- **Components of head loss**

Head loss in the pipe may be divided into the following:

– Major head loss
– Minor head loss.

Major head loss consists of loss due to friction in the pipe. Minor loss consists of loss due to change in diameter, change of velocity in bends, joints, valves, and similar items.

- **Factors affecting head loss**

Frictional head loss (h_L) in the pipe can be functionally expressed as follows:

$$h_L = f(L, V, D, n, \rho, v) \tag{4}$$

where

L length of pipe
V velocity of flow
D pipe diameter

n roughness of the pipe surface (internal surface, over which flow occurs)
ρ density of flowing fluid
ν viscosity of the flowing fluid.

The mode of action of the factors affecting head loss is as follows:

- head loss varies directly as the length of the pipe
- it varies almost as the square of the velocity
- it varies almost inversely as the diameter
- it depends on the surface roughness of the pipe wall
- it is independent of pressure.

- **Significant head loss equations** according to [5]:

– *Darcy–Weisbach formula for head loss*:

The Darcy–Weisbach formula for head loss in a pipe due to friction in turbulent flow can be expressed as

$$h_f = f \frac{LV^2}{D2g} \tag{5}$$

where

h_f head loss due to friction (m)
f friction factor (or Darcy's friction coefficient)
L length of pipe (m)
V velocity of flow (m s^{-1})
g acceleration due to gravity (m s^{-2}) = 9.81 m s^{-2}
D inner diameter of the pipe (m).

Darcy introduced the concept of relative roughness, where the ratio of the internal roughness of a pipe to the internal diameter of the pipe affects friction factor for **turbulent flow**.

– *Head loss under laminar flow—Hagen–Poiseuille equation*:

$$h_f = \frac{32\mu VL}{wD^2} \tag{6}$$

where

V velocity of flow (m s^{-1})
L length of pipe (m)
D inner diameter of the pipe (m)
w specific wt. of the fluid (kg m^{-3})
μ viscosity of the flowing fluid (kg s^{-1} m^{-2}).

Table 1 Minor loss coefficient for different fittings, after [4]

Fittings	Minor loss coefficient (c)
Fully open ball valve	0.05
Threaded union	0.08
Fully open gate valve	0.15
½ closed gate valve	2.1
Fully open angle valve	2
Threaded long radius 90° elbows	0.2
Flanged 180° return bends	0.2
Flanged tees, line flow	0.2
Threaded tees, line flow	0.9
Threaded tees, branch flow	2.0
Fully opened globe valve	10

- **Calculation of minor loss**

Minor loss can be expressed as

$$h_{\text{minor}} = c\frac{V^2}{2g} \tag{7}$$

where c is the minor loss coefficient. Thus, the total minor loss can be calculated by summing the minor loss coefficients and multiplying the sum with the dynamic pressure head. Minor loss coefficients of different components/fittings are given in Table 1.

- **How to minimizing head loss in pipes?**

One of the main aims of pipe design is to minimize the head losses associated with pipe length (frictional loss), bends, diameter change, and transitions. Minimization of head loss will keep the diameter of the pipeline to the minimum (necessary to achieve the design flow capacity), and therefore, its cost will be reduced. Head losses in the pipe can be minimized by:

- Using large diameter pipe in the mainline
- Minimizing bends or turns
- Making/selecting internal surface of the pipe smoother.

2.3 Designing Pipe Sizes for Irrigation Water Flow

Selection of pipe size should be based on the following:

- hydraulic capacity (discharge) requirement

- head loss, and
- economy.

In the short run, a small diameter pipe may require lower initial cost, but due to excessive head loss, it may require a higher cost in the long run. Pipe size based on hydraulic capacity can be found as

$$A = \frac{Q}{V} \tag{8}$$

where

Q required discharge ($\mathrm{m}^3\ \mathrm{s}^{-1}$)
A cross-sectional area of the pipe (m^2)
V permissible velocity of flow ($\mathrm{m\ s}^{-1}$).

The diameter of the pipe can be found from the relation,

$$A = \pi D^2/4 \tag{9}$$

$$D = \sqrt{\frac{4A}{\pi}} \tag{10}$$

where π represents a constant, approximately equal to 3.14159.

The pipe must have the capacity to supply peak demand (Q). After calculating the maximum size required, the second step is to calculate the head loss per unit length (say 100 m) and for the whole irrigation farm. Extra power and cost necessary for the head loss should be calculated for the entire useful life of the pipe.

3 General Considerations for Designing Surface Irrigation System

Irrigated agriculture faces a number of difficult problems in the future. One of the major concerns is the generally poor efficiency with which water resources have been used for irrigation. A relatively safe estimate is that 40% or more of the water diverted for irrigation is wasted at the farm level through either deep percolation or surface runoff. Agricultural irrigation future has many challenges, such as global warming, the low efficiency with which water resources have been used for irrigation, and 40% or more of the water diverted for irrigation is wasted through either deep percolation or surface runoff. These losses may not be lost when one views water use in the regional context since return flows become part of the valuable resource elsewhere. However, these losses often represent certain opportunities for water because they delay the arrival of water at downstream diversions and because they almost universally produce poorer quality water. One of the more evident problems in the future is the growth of alternative demands for water such as urban and industrial needs. These use to place a higher value on water resources and therefore tend to focus attention on wasteful practices. Irrigation science in the future will undoubtedly face the problem of maximizing efficiency. These losses often represent certain foregone opportunities for water because they delay the arrival of water at downstream diversions, and this produce low-quality water. The big problem in the future is the growth of alternative demands for water such as urban and industrial needs. In the future, the agriculture irrigation will undoubtedly face the problem of maximizing efficiency.

Irrigation in arid areas of the world provides two essential agricultural requirements:

- a moisture supply for plant growth which also transports essential nutrients and
- a flow of water to leach or dilute salt in the soil. Irrigation also benefits croplands through cooling the soil and the atmosphere to create a more favorable environment for plant growth [7].

- **Many decisions must be made before installing an irrigation system**

Some determinations are technical in nature, some economic, and others involve a close scrutiny of the operation and crop to be irrigated.

- Location, quantity, and quality of water should be determined before any type of irrigation system is selected. No assumptions should be made about the water supply. The challenge is technical, economical, and others like the operation and crop. And also location, quantity, and quality of water should be determined before selecting any type of irrigation system.
- Make sure that the water source is significant enough to meet the irrigation system's demand by test pumping groundwater sources or measuring flow rate of streams.
- Determination of the water advance or infiltration advance is an analysis problem, whereas computation of the inflow rate or system layout (e.g., length, width, and slope) is a design problem. The analysis of flow in surface irrigation is complex due to the interactions of several variables such as infiltration characteristics, inflow rate, and hydraulic resistance.

The design is more complex due to interactions of input variables and the target output parameters such as irrigation efficiency, uniformity, runoff, and deep percolation. In most cases, the aim of the surface irrigation system design is to determine the appropriate inflow rates and cutoff times so that maximum or desired performance is obtained for a given field condition.

- **The surface irrigation method** (border, basin, and furrow) should be able to apply an equal depth of water all over the field without causing any erosion as shown in Fig. 4.

To minimize the water percolation losses, the opportunity time (the difference between advance and recession periods—will discuss later) should be uniform throughout the plot and equal to the time required to put the required depth of water into the soil. Runoff from the field can be eliminated by controlling the inflow rate

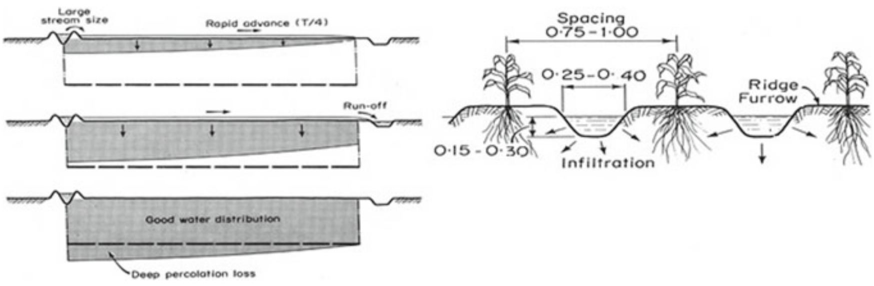

Fig. 4 Furrow irrigation: infiltration approaches

at which inflow decays with a time exactly correspond with the decay of the average infiltration rate with time for the entire length of the field. Inflow is usually cut back in discrete steps.

3.1 Variables in Surface Irrigation System

Important variables in surface irrigation system include the following: (i) infiltration rate, (ii) surface roughness, (iii) size of stream, (iv) slope of land surface, (v) erosion hazard, (vi) rate of advance, (vii) length of run, (viii) depth of flow, (ix) depth of water to be applied, (x) infiltration depth. These are schematically presented in Fig. 5a–c.

3.2 Hydraulics of Surface Irrigation System

The surface irrigation system and some of its features may be divided into the following four component systems: (1) water supply, (2) water conveyance or delivery, (3) water use, and (4) drainage. For the complete system to work well, each must work conjunctively toward the common goal of promoting maximum on-farm production. Historically, the elements of an irrigation system have not functioned well as a system, and the result has too often been very low project irrigation efficiency.

There are the following three phases of waterfront in a surface irrigation system:

- advance phase
- wetting phase (or ponding), and
- recession phase.

The advance phase starts when water first enters the field plot and continues up to the time when it has advanced to the end of the plot as shown in Fig. 6. The period between the time of advance completion and the time when the inflow is cut off or shut off is referred to as wetting or ponding or storage phase. After termination of

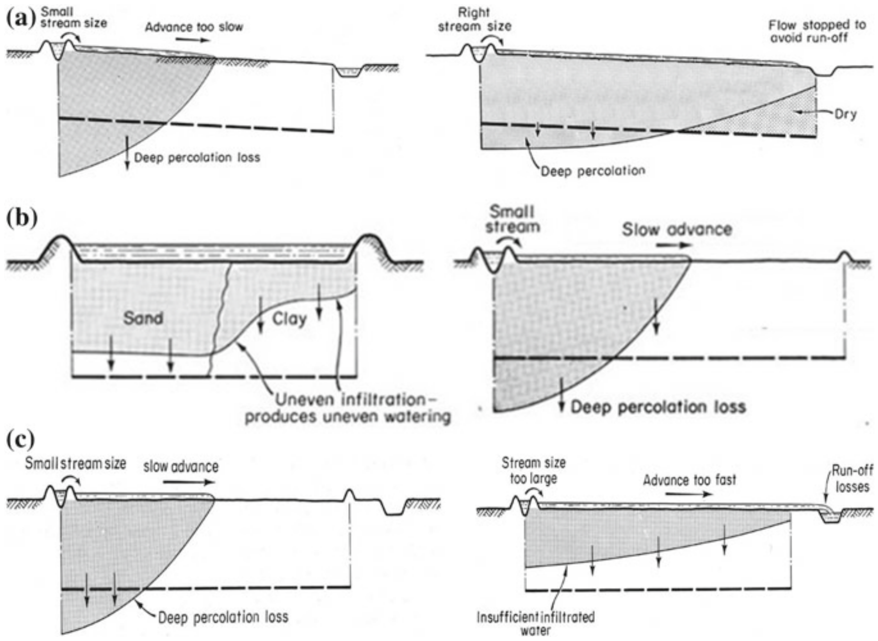

Fig. 5 **a** Furrow irrigation: problems of moisture distribution. **b** Basin irrigation: problems of moisture distribution. **c** Border irrigation: problems of moisture distribution

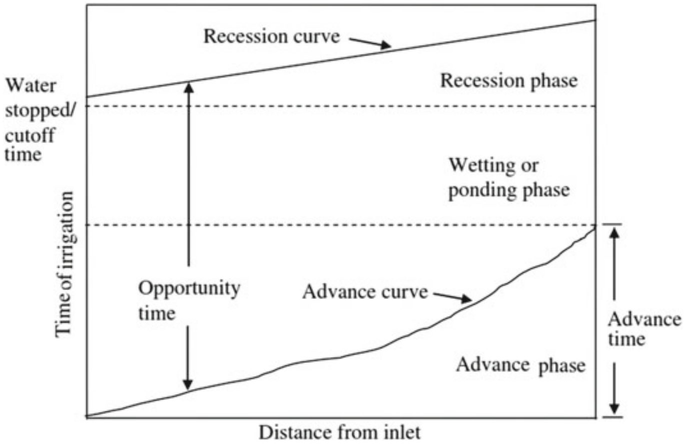

Fig. 6 Schematic presentations of phases of waterfront in surface irrigation system

the inflow, the ponding water or the waterfront recedes from the field by draining and/or into the next field by infiltration. This is the recession phase.

Unsteady overland flow analysis is required for the design and management of surface irrigation systems. When sufficient water is released over a porous medium in surface irrigation, part of this water infiltrates into the soil as shown in Fig. 4, and the remainder moves over the field as overland flow (runoff). Hydraulic analysis of surface flow during all the phases of irrigation from advance to recession is important for successful design and operation of a surface irrigation system [8].

Furrows are sloping channels formed in the soil. The amount of water that can be applied in a single application via furrow (or in other conventional surface irrigation, that is, flood or border irrigation) depends upon the ability of the soil to absorb water. The irrigation process in a furrow is identical to the irrigation process in a border, with the only difference that the geometry of the cross section, and as such the infiltration process, is different. Among surface irrigation systems, furrow irrigation with cutback is commonly used because of its potential higher irrigation efficiency, lower cost, and relative simplicity.

4 Irrigation Efficiencies

There are many ways of thinking about, determining, and describing concepts relating to irrigation efficiency. Simply speaking, the “efficiency” implies a ratio of something “in” to something “out.” Many efficiency terms related to irrigation efficiency are in use or have been proposed.

Efficiency can be measured at the scale of a whole catchment, at the individual plant scale, and at almost any level in between. The scale of measurement is of critical importance in tackling the issue of improving efficiency and must be matched with the specific objective. Commonly used irrigation efficiencies are described below.

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4.1 Application Efficiency

Water application efficiency (Ea) expresses the percentage of irrigation water contributing to root zone requirement. It indicates how well the irrigation system can deliver and apply water to the crop root zone. Hence, the application efficiency takes into account losses such as runoff, evaporation, spray drift, deep drainage, and application of water outside the target crop areas. Of these factors, deep drainage

Table 2 Attainable application efficiencies under different surface irrigation systems

Type of surface irrigation system	Attainable efficiency range (%)
Border	75–85
Basin	80–90
Furrow	65–80

and runoff are probably the major causes of inefficiency and are generally due to overwatering.

Application efficiency defined by different researchers and varies slightly in the expression [8–14]. In broad term, application efficiency is the percentage of water delivered to the field that is ready for crop use; this parameter relates the total volume of water applied by the irrigation system to the volume of water that has been added to the root zone and is available for use by the crop. Thus, the application efficiency (Ea) is calculated according to [15] as

$$\text{Ea} = (W_\text{s}/W_\text{f}) * 100 \tag{11}$$

where

Ea water application efficiency, %,

W_s irrigation water available to the crop (amount of water stored in the root zone), m^3, and

W_f water delivered to the field (amount of water added), m^3.

In simple words, irrigation water available to the crop = root zone soil moisture after irrigation − root zone soil moisture before irrigation.

Water delivered to the field = flow meter reading.

Application efficiency is primarily affected by the management of irrigation and may vary significantly between irrigation events.

Table 2 presents attainable application efficiencies under different irrigation systems (adapted from [13]).

Where the target water depth is the intended application amount, typically the soil moisture deficit amount. Thus, Potential Application Efficiency (PAE) is defined as the application efficiency when the target water depth is just satisfied (i.e., the target depth is equal to the minimum depth in the water distribution). Thus, PAE is the ratio of the target depth to the depth applied. PAE is typically used for design to assure full irrigation everywhere [10]. One of the limitations of surface irrigation is the difficulty in uniformly applying small depths of water. Surface systems are typically designed for application depths of 100 mm or more, while pressurized systems can typically be designed to apply as10 mm. When designer attempts to apply smaller depths with surface irrigation systems, the distribution of infiltrated water typically deteriorates. Therefore, one important aspect of the design is to be able to apply small depths of water uniformly.

4.2 Storage Efficiency/Water Requirement Efficiency

Storage efficiency indicates how well the irrigation satisfies the requirement to completely fill the target root zone soil moisture. Thus, storage efficiency (ES) is represented as

$$\text{ES} = (\text{change in root zone soil moisture}) \times 100/(\text{target change in root zone soil moisture}) \tag{12}$$

where the change in the root zone soil moisture content is not measured directly, the storage efficiency can be approximated by relating the average depth of water applied over the field to the target root zone deficit. The root zone deficit is calculated using soil type, crop root zone, and soil moisture content data. In this case, the storage efficiency is calculated as

$$\text{ES} = (\text{average depth applied}) \times 100/(\text{root zone deficit}) \tag{13}$$

The maximum storage efficiency is 100%. Calculations with a result above 100% indicate losses due to runoff or deep drainage [10].

4.3 Irrigation Distribution Uniformity

Irrigation uniformity is a measure of how uniform the application of water is to the surface of the field. That is, an expression describes the evenness of water applied to a crop over a specified area, usually a field, a block, or an irrigation district. The value of this parameter decreases as the variation increases.

Distribution uniformity is primarily influenced by the system design criteria. Poor uniformity of application is often easily identified by differences in crop response and/or evidence of surface waterlogging or dryness. The part of the field receiving more than the average depth may suffer from inefficiencies due to waterlogging and/or runoff, while the other part receiving less than the average may suffer from undue water stress. Thus, uniform irrigation is important to ensure maximum production and minimum cost.

An important component of the evaluation of in-field irrigation performance is the assessment of irrigation uniformity. If the volume of water applied to a field is known, then the average applied in depth over the whole field can be calculated. In most cases, one half of the field receives less than the average depth and one half more than the average depth applied. Hence, if the average volume applied is the target application required to meet the crop requirements, one half of the field has been over-irrigated (reducing the efficiency of application), while the other half of the field has been under-irrigated (potentially reducing yield). Thus, a major aim of irrigation management is to apply water with a high degree of uniformity while keeping wastage to a minimum.

4.4 Uniformity Coefficient

Uniformity coefficient, introduced by Christiansen [16], it is defined as the ratio of the difference between the average infiltrated amount and the average deviation from the infiltrated amount, to the average infiltrated amount. That is

$$\mathrm{UCC} = \left[\frac{\sum_{i=1}^{i=N} Z_i - Z_{\mathrm{av}}}{Z_{\mathrm{av}} * N} \right] * 100 \tag{14}$$

where

UCC	Christiansen uniformity coefficient (or simply uniformity coefficient)
Z_i	infiltrated amount at point i
Z_{av}	average infiltrated amount
N	number of points used in the computation of UCC.

Christiansen developed uniformity coefficient to measure the uniformity of sprinkler systems, and it is most often applied in sprinkler irrigation situation. It is seldom used in other types of irrigation. Values of UCC typically range from 0.6 to 0.9.

4.5 Low-Quarter Distribution Uniformity

Low-quarter distribution uniformity ($\mathrm{DU}_{\mathrm{lq}}$) is defined as the percentage of the average low-quarter infiltrated depth to the average infiltrated depth as [10]:

$$\mathrm{DU}_{\mathrm{lq}} = 100 * \frac{\mathrm{LQ}}{M} \tag{15}$$

where

$\mathrm{DU}_{\mathrm{lq}}$	distribution uniformity at low quarter (or simply distribution uniformity, DU)
LQ	average low-quarter depth infiltrated (mm)
M	average depth infiltrated (mm).

The "average low-quarter depth infiltrated" is the average of the lowest one-quarter of the measured values where each value represents an equal area.

For calculation of DU of low one half, substitute "low quarter" by "average low half depth received or infiltrated." has been applied to all types of irrigation systems.

In trickle irrigation, it is also known as "emission uniformity." In sprinkler situation, it is termed "pattern efficiency."

The DUlq, the relationship between DU and UCC, can be approximated as follows [17]

$$\mathrm{UCC} = 100 - 0.63(100 - \mathrm{DU}) \tag{16}$$

$$\mathrm{DU} = 100 - 1.59(100 - \mathrm{UCC}) \tag{17}$$

5 Performance Evaluation

Describe how to determine the performance of basin/furrow irrigation. It is assumed that the net irrigation water need of the crop is known (i.e., the net irrigation depth). This is compared with what happens during the actual irrigation practice. Field application efficiency thus obtained is a good measure for the evaluation of the performance.

5.1 Concept, Objective, and Purpose of Performance Evaluation

- **Concept**

Performance terms measure how close an irrigation event is an ideal one. An ideal or reference irrigation is one that can apply the right amount of water over the entire area of interest without loss. Evaluation is a process of establishing a worth of something. The "worth" means the value, merit, or excellence of the thing.

Performance evaluation is the systematic analysis of an irrigation system and/or management based on measurements taken under field conditions and practices are normally used and comparing the same with an ideal one. Traditionally, irrigation audits are conducted to evaluate the performance of existing irrigation systems. A full irrigation audit involves an assessment of the water source characteristics, pumping, distribution system, storage, and in-field application systems. However, audits are also conducted on several components of the on-farm irrigation system [18].

- **Objectives**

The modernization of an irrigated area must start with a diagnosis of its current situation. Following this procedure, the specific problem affecting water use can be addressed and that may lead to a feasible solution. The specific objectives of performance evaluation are as follows:

- To identify the causes of irrigation inefficiencies
- To identify the problem/weak point of irrigation management
- To diagnose the water management standard of the irrigation project
- To determine the main principles leading to an improvement in irrigation performance.

- **Purpose of performance evaluation**

The purpose of performance assessment is to measure, through consistently applied standards, various factors that indicate either by comparison across systems whether a system is performing "well" or "badly" in a relative sense or by a system-specific analysis to see how the system is operating in relation to its own objectives [19]. The specific purposes are as follows:

- to improve irrigation performance
- to improve management process
- to improve the sustainability of irrigated agriculture.

- **Benefits of evaluation**

Evaluation leads to the following benefits:

- Improved quality of activities
- Improved ability of the managers to manage the system
- Savings of water and energy
- Ensure maximum production/benefit and minimum cost.

- **Factors affecting irrigation performance**

The performance of an irrigation system at field scale depends on several design variables, management variables, and system variables *or* factors. These factors characterize an irrigation event. Mathematically, it can be expressed as

$$P_{\mathrm{ir}} = f(q_{\mathrm{in}}, A, L, W, N, S_0, I_n, t_{\mathrm{cutoff}}, S_{\mathrm{w}}, D_{\mathrm{ru}}, P, R_{\mathrm{d}}, \mathrm{ET}, \ldots) \tag{18}$$

where

P_{ir}	performance of an irrigation event
f	function
q_{in}	inflow rate or application rate (to the furrow or per unit width of border or basin)
A	sectional form of the unit plot to be irrigated (especially for furrow)
L	length of run of the flow
W	width of the section *or* unit plot
N	roughness coefficient of flow for the plot (Manning's N)
S_0	longitudinal slope of the plot
I_{n}	infiltration characteristics of the soil
t_{cutoff}	time cutoff

S_{w}	soil water status at the time of irrigation (i.e., condition of deficit)
D_{ru}	reuse of drainage runoff (if applicable)
P	pressure of the flow system (especially for gated/perforated distribution pipes)
R_{d}	root zone depth of the crop during the irrigation event
ET	atmospheric water demand or evapotranspiration demand.

5.2 Performance Indicators

Activities of irrigation systems start at the point of water supply headwork or pump. Impacts of irrigation are not limited to the field but also extend to the socioeconomic conditions of the target audience. In general, a set of indices or indicators are used for evaluating the performance of an irrigation scheme. Indicators are termed as performance indicators. No single indicator is satisfactory for all descriptive purpose. Moreover, there are uncertainties about the exact values of some indicators. Several indicators can give an overall picture of the irrigation project. Typically, high engineering efficiency implies a reduction of losses. Beneficial uses include crop water use, salt leaching, frost protection, crop cooling, and pesticide and fertilizer applications [20]. For convenience in understanding and application, the indicators can be grouped as

- Engineering
- on-farm water use indicators
- Crop and water productivity
- Socioeconomic.

5.3 Engineering Indicators

Engineering indicators are those which are related to pump, water headwork, water supply, water conveyance system, and energy use [4, 21]. Indices under this category include the following:

– Pumping plant efficiency	– Headwork’s efficiency
– Water conveyance efficiency	– Water delivery performance
– Irrigation system efficiency (or overall efficiency)	– Equity of water delivery
– Channel density	– Water supply—requirement ratio
– Water availability and shortage	– Energy use efficiency

5.4 On-Farm Water Use Indicators

These indicators concern the efficiency of on-farm water application and the uniformity of water distribution along the irrigated field. Indicators under this category are as follows:

– On-farm water loss	– Deep percolation fraction/deep percolation ratio
– Runoff fraction/tail-water ratio	– Water application efficiency
– Storage efficiency/water requirement efficiency	– Application efficiency of low quarter
– Distribution efficiency or uniformity	– Low-quarter distribution uniformity

5.5 Crop and Water Productivity

Indicators under this category are as follows:

– Area irrigated	– Irrigation intensity
– The duty of discharge/supply water	– Crop productivity (yield rate)
– Water productivity	– Irrigation water productivity

5.6 Socioeconomic Indicators

In some cases, cost–benefit or social uplift and social acceptance aspects are measured. These are called socioeconomic indicators. Indicators under this category include the following:

– Irrigation benefit–cost ratio	– Cost per unit production
– Irrigation cost per unit area	– Farmers income ratio

6 Ideal Situation for Estimation of Irrigation System

The field (soil) and crop condition should represent the ideal/normal field condition during the evaluation of an irrigation system. The conditions can be summarized as follows:

(a) The field soil should be stable, not new, refilled, or a developed one.
(b) The crop condition should be representative, not just after emergence or at ripening stage but in between (good coverage).
(c) The soil should be dry enough—appropriate time for irrigation.
(d) Water supply/water pressure should be sufficient enough to apply inflow the designed rate.

7 Performance Assessment of Surface Irrigation System

- **Pumping plant evaluation**

Pumping system efficiency can contribute substantially to energy saving. Pumping plant evaluation requires a pump test, which checks the flow rate capacity, lift, discharge pressure and/or velocity, rated discharge capacity, and input horsepower.

Pump discharge can be measured by flow meter (in the vicinity of the pump outlet), flume, or by the coordinate method [22]. The rated discharge capacity of the pump can be read from the manufacturer's manual *or* the pump rating written on the pump body. If a mechanical engine is used to power the pump, its capacity can be read from its rating seal or manual. If an electrical motor is used to operate the pump, power consumption by the motor can be measured by "Clip-On meter" or "Multi-meter" or from the change in power reading in the "electric meter" for a certain period. Rated capacity of the motor can be read from its body.

Knowing the above information, overall pumping plant efficiency and efficiency of each component (such as motor or engine efficiency, pump efficiency) can be calculated.

7.1 Border Irrigation Evaluation

Field observations and measurements required for conducting a border irrigation system evaluation include the following:

– Border dimension	– Advance phases and time
– Slope of the border	– Recession time
– Inflow rate	– Topography of the field
– Runoff rate and volume (if any)	– Crop type and stage of the crop
– Irrigation time (duration)	

The measurement steps and procedures are as follows:

- The border dimensions can be measured using a "measuring tape."
- Soil surface elevations (at different points, 10–30 m intervals along the borders) can be determined using a "total topographic station" or "level instrument." Slope and standard deviation of soil surface elevations can be determined from the measured data.
- The "inflow" or "irrigation discharge" can be measured using suitable flow measuring devices such as mini-propeller meter and flume.
- The advance phase can be determined from the recording of the advance time to reference points located along the border (every 10–30 m).
- A number of flow depth measurements are to be performed across the border, every 5–10 m. The average of all measurements is used to represent the flow depth at this point and time.
- The flow depth at the upstream end of the border is to be measured shortly before the cutoff.
- In the open border, surface runoff (if conditions permit) is to be monitored. The runoff can be measured using the mini-propeller meter or a flume.
- A hydrograph is to be established from discharge measurements, and it is time for integration will yield the runoff volume.
- Infiltration in "ring infiltrometer" and border infiltration can be correlated, and a relationship can be established. Then, the infiltration parameters can be determined.
- To estimate the infiltrated depths of water (required for computing uniformity and efficiency indices), field data from the evaluation can be utilized to derive the infiltration parameters of a Kostiakov type infiltration equation. The infiltration parameters (K, a) and roughness coefficient (N) can be determined through the solution of inverse surface irrigation problem [23].
- For that, a hydrodynamic one-dimensional surface irrigation model (e.g., SIRMOD) can be used. Such a model is to be executed using tentative values of the coefficient "K" and the exponential "a" from the Kostiakov infiltration equation and the Manning's N. The parameters should be adjusted until the model satisfactorily reproduces the experimental values of flow depth and irrigation advance for each evaluation [24].
- Performance indices—application efficiency and the low-quarter distribution uniformity—should be determined using the formula described in an earlier.

7.2 Basin Irrigation Evaluation

Basins have no global slope, but the undulations of the soil surface can have an important effect on the advance and recession process of an irrigation event.

For evaluation of basin irrigation, measurements should be made during representative irrigation events. The required measurements are as follows:

- advance, water depths at selected locations
- surface drainage or recession commonly measured performance indices for basin irrigation are as follows:
- application efficiency
- distribution uniformity
- deep percolation ratios
- requirement efficiency or storage efficiency.

For basin irrigation, tail-water ratio is zero. [25] defined the distribution uniformity (DU) for basin irrigation.

7.3 Furrow Irrigation Evaluation

Generally, the evaluation of furrow irrigation system is restricted to a single or small number of adjacent furrows due to the intensive measurement process. Complete inflow, advance, and runoff measurements are used to accurately determine soil infiltration rate for a small number of furrows.

The working step and procedures for the evaluation of furrow irrigation system are as follows:

- Measure the length and spacing of furrow.
- Measure soil moisture (before irrigation).
- Install the equipment (e.g., flume, scale, moisture measuring equipment).
- Start irrigation.
- Record the flow rate (at 5–10 min intervals, until the constant flow rate is achieved).
- Record the advance data after 6, 12, and 24 h from the starting of irrigation.
- Record the water depth at different points (10, 20, 50 m) at several time intervals.
- Record the cutoff time.
- Record recession data (water depth) at several distances (10, 20, 50 m) from the starting point at several time intervals.
- Record the depth of ponding at lower ¼ the part of the furrow.
- Record the runoff volume (if the process permits).
- Measure soil moisture up to the desired depth (root zone) at different points throughout the furrow after reaching field capacity.
- Determine the wetted cross section of the furrow at several sections and average them.

Volume balance approach can be applied to find out different components of water balance (e.g., infiltration, deep percolation). Volume balance approach is based on the principle of mass conservation. At any time, the total volume of water that has entered the furrow must be equal to the sum of the surface storage, subsurface storage (infiltrated), deep percolation (if any), and runoff (if any).

8 Improving Performance of Surface Irrigation System

Improving the performance of an irrigation system is to take remedial measures for correcting the fault/deficiency, which has been identified during evaluation/diagnosis process. Besides, a number of techniques can be used in the design of a system to increase its uniformity and efficiency [26] Mentioned that for surface irrigation systems, the inflow rate could be matched with the soil intake rate, slope, and length of the run; the cutoff time can be matched thereby. Another technique is that water use is more efficient with afternoon irrigation as the evaporative loss is minimal. Some common problems/faults and suggestive measures for improving the performances are summarized according to [27]:

- Pumping plant efficiency is low:
  - Renovate the moving parts
  - In case of deep well, wash out the well screen
- Water conveyance efficiency is low:
  - Renovate/perform lining the conveyance channel
  - Reduce the field channel density
- Water delivery performance is not satisfactory:
  - Perform efficient/economic channel design
  - Recast/ensure delivery system
- Channel density is high:
  - Reduce the channel length by straightening through the command area
- On-farm water loss is high:
  - Compact the borders of each plot
  - Improve the water-holding capacity of the soil by adding organic manures
  - Reduce relative percentage of sand by adding silt or clay soil
- Water supply—requirement ratio is not good:
  - Recast the supply amount, or
  - Change the cropping pattern (if possible), altering high water-demanding crops, or

  - Search for new source of supply

- Deep percolation:
  - Line the channels soil
- Runoff fraction is high:
  - Maintain correct slope of land
  - Apply correct flow rate and time for flow (cutoff time)
  - Take care of the borders; construct high barriers
- Water application efficiency is low:
  - Minimize on-farm water loss
  - Estimate correct amount of water demand
  - Apply correct flow rate based on infiltration characteristics
  - Level the land with appropriate slope
  - Maintain correct slope of the water run considering infiltration rate and flow rate
  - Improve water-holding capacity of the soil
- Water storage efficiency is not satisfactory:
  - Correctly estimate the crop root zone depth before irrigation
  - Estimate correct amount of water demand
- Distribution uniformity is low (poor distribution of infiltrated water over the field):
  - Apply correct flow rate based on infiltration rate and
  - the slope of the run
  - Design the length of run based on infiltration rate, slope,
  - flow rate
  - Cut off the flow at proper time
- Low-quarter distribution uniformity is low:
  - Apply correct flow rate based on infiltration rate
  - Design the length of run based on infiltration rate, slope, and flow rate
  - Cut off the flow at proper time (after reaching the waterfront at tail end)
- Area irrigated per unit flow (Duty) is not satisfactory:
  - Reduce conveyance, seepage, and percolation loss
  - Schedule irrigation properly (apply correct amount of water based on need)
  - Improve water-holding capacity of the soil
- The intensity of irrigation is low:
  - Reduce all possible losses
  - Increase irrigation efficiency
  - Schedule crops and crop rotations

- Crop productivity is low:
  - Ensure proper irrigation
  - Ensure proper management of other inputs (like balance fertilizer)
  - Ensure other cultural management (proper population, weeding, pesticide, and insecticide application, if needed)
- Water productivity is below the normal range:
  - Schedule irrigation properly
  - Reduce tail-water runoff
  - Minimize on-farm water loss
  - Maximize utilization of stored soil moisture
  - Ensure other crop management aspects
- Irrigation water productivity is below the desired limit:
  - Schedule irrigation properly
  - Reduce tail-water runoff
  - Minimize on-farm water loss
  - Maximize utilization of stored soil moisture
  - Ensure other crop management aspects
- Irrigation benefit–cost ratio (B–C ratio) is low:
  - Minimize irrigation cost by proper scheduling and reducing all sorts of water loss
  - Maximize production by proper management of other inputs and selecting appropriate crop type and variety
  - Maximize utilization of stored soil water and rainwater, if available
- Cost per unit production is high:
  - Similar to that of B–C ratio
- Irrigation cost per unit area is high:
  - Similar to that of B–C ratio
- Farmer’s income ratio is not satisfactory:
  - Similar to that of B–C ratio.

9 Case Studies from Egypt

9.1 Improving Irrigation Efficiency

Because crop irrigation is practiced in areas with dry climates under climate changes, much of the water use in those areas is for agriculture. Most of the irrigation systems are surface or gravity systems, which typically have efficiencies of 50–60%. This means that 40–50% of the water applied to the field is used for evapotranspiration by the crop, while 40–50% is "lost" from the conveyance system, by surface runoff from the lower end of the field, and by deep percolation of water that moves downward through the root zone as shown in Fig. 7.

Increased irrigation efficiencies allow farmers to irrigate fields with less water, which is an economical benefit. Also, increased irrigation efficiencies generally mean better water management practices, which, in turn, often give higher crop yields [28]. Thus, increasing field irrigation efficiencies also saves water by increasing the crop production, thus allowing more crops to be produced with less water [29].

Field irrigation efficiencies of gravity systems can be increased by better management of surface irrigation systems (changing rate and/or duration of water application), modifying surface irrigation systems (changing the length or slope of the field, including using zero slope or level basins). Surface irrigation systems often can be designed and managed to obtain irrigation efficiencies of 80–90%.

Thus, it is not always necessary to use a sprinkler or drip irrigation systems when high irrigation efficiencies are desired.

First applied of the method and evaluated at different sites in Egypt to enhance water application efficiency (Ea), storage efficiency (Es), and water distribution uniformity as shown in Figs. 8, 9, and 10. Through controlled PVC, spill pipes with 1 m length and 63 mm diameter installed in the ditch of irrigation canal against the upper ridge of the field, which convey the water according to the required flow rate (one spill pipe for each furrow). The temporary dam (barrier) was used (if needed) to keep a constant hydraulic head above the inlets of a group of spill pipes to realize inflow rate adequately for each spill pipe (equal inflow rate each furrow) during irrigation events.

Fig. 7 Irrigation with traditional borders system using an open excavation channel

Fig. 8 Preparation and installation of spill pipes

Fig. 9 After operation with long furrows irrigation system

The number of spill pipes (each group of furrows) determined to depend on the gross water discharge pass in irrigation channel by gravity.

The operating technique of the developed system starts with the water spill pipes being closed until the water height reaches in the channel above the level of the spill pipes at least 12 cm (through the temporary dam in the irrigation channel.) At that time, the farmer can remove the plastic caps to allow water to pass and start irrigation, by ensuring that outflow will be equally behind a number of spill pipes. Before opening the second group of spill pipes which it was closed previously, the farmer firstly must be waiting to re-rise the water level in irrigation channel as shown before and so on during the third group of spill pipes until finishing the irrigation event. By this method of operating technique the water will distribute in equal flow rates to irrigated furrows and/or borders with shorter advance times. [30] showed

Fig. 10 After installation and evaluated of spill pipes with excavated channel

that more water losses by deep percolation in the soil especially occurred in first and second watering events as shown in Figs. 11 and 12.

Second applied of the method and evaluated at different sites in Egypt to enhance irrigation performance as shown in Fig. 13 by the simple fabricated way.

When irrigation water directed from the pumping unit (the control head) to the farm by network pipelines and control valves. Thus, more PVC pipe diameters (110–160 mm) can use and fabricate as shown in Fig. 13 using outflow orifices each 72 cm for fixation one PVC Nibble each orifice with controlled by PVC cap easy take off during watering, this method of controlled perforated pipes (CPP) was used and evaluated instead of metal gated pipes.

Fig. 11 During irrigation with long borders system

Fig. 12 After operation with long border irrigation system

Fig. 13 Preparation and collection of controlled perforated pipes (CPP)

The group of controlled orifices number opened depending on the general flow directed to the irrigation site as shown in Figs. 14 and 15.

The results of long evaluation periods through different research studies at different sites in Egypt as [13, 31, 32] proved that the positive effects on different field crops yields cultivated under various conditions with improved management practices compared with traditional management were significant increases.

9.2 Some of the Obstacles and Constraints

(a) **Financial/economic**

- Certain **water conservation/demand management (WC/DM)** measures depend on financial outlay by end users, who may not have adequate resources
- Water is allocated to consumers irrespective of economic value or efficiency of use
- Water institutions own water supply infrastructures

Fig. 14 During irrigation with long borders system

Fig. 15 During irrigation with two long borders system (CPP) instead of excavation open channel

- Lack of funding or disproportionate funding for supply-side measures at the expense of WC/DM.

(b) **Technical/institutional**

- lack of adequate knowledge of the cause of growth in demand
- current planning practices choose the cheapest solution without regard to operating costs
- lack of understanding of the consumer and water usage patterns
- lack of cooperation among local authorities
- lack of cooperation among water services institutions
- officials and industry sectors protect their interests.

10 Conclusions

Egypt is highly vulnerable to climate change, which increases the water demand and causes a loss of crops. Thus, one of the main challenges facing the sequential government during the previous decades was to enhance the agriculture sector by increasing the efficiency of water use.

Irrigation efficiency is greatly dependent on the type and design of water conveyance and distribution systems. Designing of economic pipe diameter is important to minimize cost, water loss, and land requirement.

To achieve high performance in surface irrigation system, it must be designed to irrigate uniformly, with the ability to apply the right depth at the right time. Properly designed, installed, maintained, and managed irrigation system greatly reduce the volume of irrigation water and hence save energy and money. Besides, it improves the crop yield and quality.

Developed water distribution systems are more effective, efficient, and far better than the conventional system, and developed water distribution systems at different locations in the country are running in good condition without any major constraint.

This developed distribution system could be widely adopted as a model in the field for increasing agricultural production in Egypt. Among all the water distribution systems, the PVC pipe line system is the most suitable. Improved and efficient water management practices can help to maintain farm profitability in an era of increasingly limited and more costly water supplies.

11 Recommendations

Evaluation helps to identify the problems resulted from mismanagement and the measures required to correct them. No single indicator is satisfactory for all descriptive purposes.

In general, a set of indices are used for evaluating the performance of surface irrigation system. Most commonly used indices are described in this chapter. Of course, adequate monitoring and evaluation of performance are needed to improve water management practices in order to achieve an increase in overall efficiency.

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