

Drip Irrigation Technology: Principles, Design, and Evaluation



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1 Introduction

The steady increase in population is an urgent factor for increasing agricultural production to provide food in the world to cope with this increase in the population. Increasing agricultural production requires horizontal expansion by adding new lands, which will require additional water to meet the irrigation needs of different crops. This expansion requires the search for new sources of water and rationalizing the use of available water, which has become a priority for planners and officials in the agricultural and water sectors in all countries of the world [1].

Traditional and non-conventional water sources in Egypt are limited and are growing scarcer year after year. The limited share of the Nile water that Egypt receives is not expected to increase in the future. The lack of these resources and sometimes their scarcity, coupled with the continuous decline in the quality of water used in irrigation, has created an urgent need for research and development in irrigation technology to provide water and energy, improve field management of water, and optimize the use of water resources. That is because the agriculture consumes more than 85% of the total demand for water. Drip irrigation is one of the modern innovations of irrigation—which is undoubtedly a clear advance in irrigation technology [1, 2].

Perhaps one of the most important methods of modern irrigation technology represented in the system of drip irrigation achieved some of these demands and avoided some of the disadvantages that emerged with other irrigation methods. Drip irrigation is one of the modern innovations of irrigation—which is undoubtedly a clear advance in irrigation technology [1].

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The design and evaluation of drip irrigation system are described briefly in this chapter. Sufficient information is presented to familiarize the reader with:

1. Definition of drip irrigation system.
2. The benefits and problems of the drip irrigation system.
3. The latest types of drip irrigation system in Egypt.
4. The major components of drip irrigation systems.
5. Design and evaluation steps of drip irrigation system.

2 Drip Irrigation

Drip, trickle, localized, or pressurized irrigation, by definition, is an irrigation technology. Irrigation water and chemical solutions are connected to drip irrigation systems in the quantities required and calculated accurately and at slow rates in the form of separate or continuous points using mechanical tools known as pointers placed at specific points along the water supply lines. The rate of disposition of these filters ranges from 1 to 12 L/h. In this method, the root zone is wetted only with the rest of the soil surface. This is done for both vegetable plants and fruit trees, but with varying water rates. The method of drip irrigation is characterized by slowly adding water to the plant at intervals between twice a day and once every three days, depending on the type of plant, soil type, and climatic conditions. Fertilizers and some chemicals can also be delivered through a high-efficiency drip irrigation method for each plant. Drip irrigation can be applied in the field above the soil surface or under the soil surface. The water distributed through the network drip irrigation pipes to pressure ranging from 15 to 200 kPa [1, 3].

Drip irrigation is superior to other irrigation methods (surface irrigation and sprinkler irrigation), which can be used very efficiently in sandy soil and fields with different terrains. It can also be used in the arid and wetland. Well-designed drip irrigation provides up to 50% water content compared to surface irrigation and 30% compared to spray irrigation by reducing water losses that are lost by deep leakage, surface runoff, or evaporation in other irrigation methods. Drip irrigation provides energy because it works at low operating pressure compared to sprinkler irrigation systems [1, 3].

The method of drip irrigation has spread in many countries such as America, Australia, Mexico, and England, and recently spread in the reclamation lands in Egypt. One of the first countries to consider this system was England in 1945, where it began to be used only in the field of experiments and then expanded to be used in irrigation. Then came Australia, America, and Israel, where its use in Israel increased widely in the late 1960 and early 1970 [2].

In Egypt, a drip irrigation system was designed, constructed, and tested for the first time in 1975 by El-Awady et al. [4]. The system used micro-tube emitters under the low head, thus reducing amenability to clogging among other advantages.

Previously, the term “micro-irrigation” has recently emerged. It is more comprehensive than drip irrigation and is used to describe the irrigation method which is characterized by the following [3, 5]:

1. The application of water at low rates.
2. The application of water over long irrigation time.
3. The application of water at frequent intervals.
4. The application of water directly near or into the plant root zone.
5. The application of water by low operating pressure delivery system.
6. Water is used to transport fertilizers and other agricultural chemicals to plants.

The term “micro-irrigation” describes a family of irrigation systems that apply water through small devices. These devices deliver water onto the soil surface very near the plant or below the soil surface directly into the plant root zone. Growers, producers, and landscapers have adapted micro-irrigation systems to suit their needs for precision water application. Micro-irrigation systems are immensely popular not only in arid regions and urban settings but also in sub-humid and humid zones where water supplies are limited or water is expensive. In irrigated agriculture, micro-irrigation is used extensively for row crops, mulched crops, orchards, gardens, greenhouses, and nurseries. In urban landscapes, micro-irrigation is widely used with ornamental plantings, <http://www.durhampump.com/irrigation/micro-system/>.

Micro-irrigation can be defined as the slow application of water on, above, or below the soil by surface drip, subsurface drip, bubbler, and micro-sprinkler systems. Water is applied as discrete or continuous drips, tiny streams, or miniature spray through emitters or applicators placed along a water delivery line adjacent to the plant row [3].

3 Drip Irrigation Types

3.1 Surface Drip Irrigation System

The surface drip irrigation system is a type of micro-irrigation. This system uses emitters and lateral lines laid on the soil surface or attached above ground on a trellis or tree (Fig. 1). Surface drip irrigation is widely used to irrigate perennial crops (tree and vines) and annual row crops [3]. Generally, discharge rates are less than 12 L/h for point source emitters and less than 12 L/h m for line source emitters. The advantages of surface drip irrigation system are easy installation, inspection, maintenance, cleaning, and changing emitters, in addition to the possibility of observing the wetting patterns on soil surface and measuring the discharge rates of individual emitters. On the other hand, the lateral lines of this system can interfere with some agricultural processes such as plowing, harvesting, and others [6].



Fig. 1 Surface drip irrigation

3.2 Subsurface Drip Irrigation System

This technology has gathered momentum during the last two decades. Subsurface drip irrigation system is a type of micro-irrigation. It is defined as the application of water below the soil surface by buried emitters (Fig. 2). The discharge rate of emitters for subsurface irrigation system is generally in the same range as those for surface drip irrigation rates and is usually less than 7.5 L/h. This system is suitable for a wide variety of horticultural and agronomic crops and, in many respects, is applicable to those crops presently under surface drip irrigation. The advantages of the subsurface drip irrigation system are negligible interference with farming activity, elimination of mechanical damage to laterals, decreased weed infestation, elimination of runoff, and evaporation from the soil surface may be zero, and improved uptake of nutrition elements by the roots, notably phosphorous. The disadvantages are high costs for burying the laterals into the soil, plugging hazard by intruding roots and sucked-in soil particles, inconvenience in monitoring the performance of drippers and laterals, and strict maintenance is mandatory [3, 6, 7].

3.3 Bubbler Irrigation System

In bubbler irrigation, water is applied to the soil surface as a small stream or fountain to flood small basins or the soil adjacent to individual trees, typically from a small diameter tube 1–13 mm or commercially available emitters, where the discharge rates of these emitters are less than 250 L/h (Fig. 3). Because the emitter discharge



Fig. 2 Subsurface drip irrigation

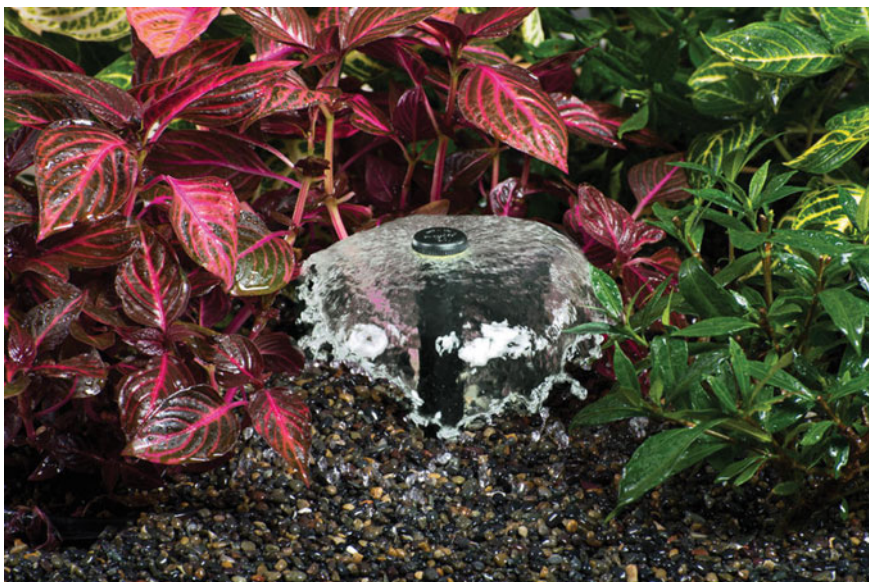


Fig. 3 Bubbler irrigation system

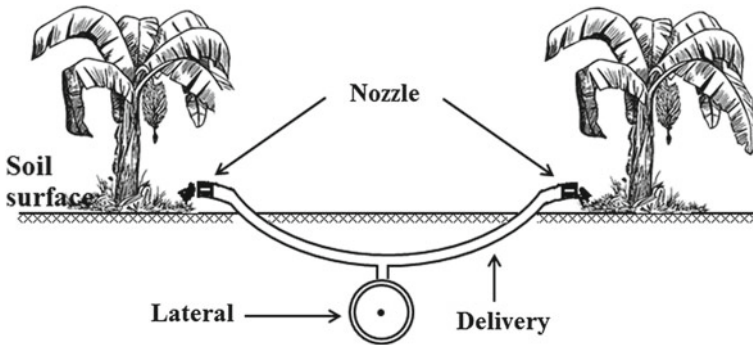


Fig. 4 Typical installation of new bubbler irrigation system [8]

rate normally exceeds the infiltration rate of soil, a small basin or furrows are usually required to contain the water or control the runoff and erosion. Because of the large diameter tubes, bubbler systems are not as prone to clog and normally have higher discharge rates than surface and subsurface drip systems. Operating pressure for bubbler irrigation system is ranging from 100 to 300 kPa. This system is well suited for perennial crops, particularly on orchards and vineyards with level topography [3, 6].

The advantages of bubbler irrigation are reduced filtration, maintenance or repair, and energy requirements compared with other types of drip irrigation systems. However, larger size lateral lines are usually required with the bubbler systems to reduce the pressure loss associated with the higher discharge rates [3].

In recent decades in Egypt, a bubbler irrigation system has been used successfully in Faiyoun Governorate for the irrigation of fruit trees. Also, in 1999 at Valoga Village, South Tahrir, Behera Governorate, Egypt, Elmesery [8] studied and evaluated a new design and installation of low head bubbler irrigation, which can use drip irrigation networks with available materials to irrigate banana trees (Fig. 4). The method uses nozzles which can be conveniently adjusted for uniformity. The development of a bubbler system can easily be adjusted for uniformity by changing of the nozzle, sizes along laterals, according to the following equations [8]:

In the case of single delivery:

$$dn_n = \left[\frac{q_d}{6.31g^{0.5}(HE_n/L)^{0.5}d^{1.14}} \right]^{0.735} \quad (1)$$

In the case of two deliveries:

$$dn_n = \frac{q_d L^{0.5}}{4.7g^{0.5}d^{1.5}(HE_n)^{0.5}} \quad (2)$$

where dn_n is the nozzle diameter (cm), q_d is the delivery discharge (cm^3/s), g is the gravitational acceleration (cm/s^2), HE_n is the effective head (cm), L is the delivery length (cm), and d is the delivery diameter (cm).

3.4 Micro-sprinkler Irrigation System

Micro-sprinkler irrigation is also called spray irrigation. In micro-sprinkler irrigation, water is sprayed on the soil surface near individual trees as a small spray, jet, fog, or mist, where the water travels through the air becoming instrumental in the distribution of water (Fig. 5). Discharge rates for point source spray emitters (micro-sprinklers) are generally less than 175 L/h. Micro-sprinkler irrigation system is primarily used to irrigate trees and vine crops. Micro-sprinklers can be spaced to cover the entire land surface as with conventional sprinkler systems or a portion of the land surface like other trickle systems. The primary advantage of spray over bubbler irrigation is lower application rates which decrease the potential for runoff and erosion. Losses due to wind drift and evaporation are, however, greater with spray irrigation than with other drip systems [3, 6].



Fig. 5 Micro-sprinkler irrigation system

3.5 Mobile Drip Irrigation System (MDIS)

The idea of a mobile drip irrigation system (MDIS) is a combination of several advantages of the stationary drip irrigation with the lateral move irrigation system as center pivot, linear move, or boom trailer irrigation machines. Generally, MDIS combines the efficiency of surface drip irrigation (95%) with the flexibility and economics of center pivot irrigation. Crops can be effectively irrigated at very low liters per minute well deliveries. MDIS is combining the labor-saving advantages of the mobile and semi-mobile irrigation methods with the water- and energy-saving effects of drip irrigation system [1, 9–11].

The use of drip tubes with a moving irrigation system appears firstly introduced in 1974 by Rawlins et al. [12] which combined several advantages of drip irrigation system and lateral move systems. Efforts were made to commercialize the technology as early as 1992 under the name of Drag-N-Drip by Sherman Fox of Trickle Irrigation Specialties Co. of Salt Lake City, Utah. Newer efforts at commercializing the technology are being made by T-L Irrigation of Hastings, Nebraska (www.tlirr.com), under the trade name of Precision Mobile Drip Irrigation (PMDI), which utilizes in-line drip hoses to distribute water directly to the ground [10, 13, 14].

In Egypt, a linear mobile drip irrigation system (MDIS) was designed, built by using classic dripping irrigation materials and tested on pea crop for the first time in 2016 by Fayed [15] in the research field of Water and Irrigation Systems Engineering Department, Faculty of Agricultural Engineering, Al-Azhar University, Nasr City, Cairo, Egypt.

The linear mobile drip irrigation system (MDIS) is designed generally and assembled as shown in Figs. 6 and 7 [15]. It includes two towers with four driven wheels for moving the system in a linear desired direction. The towers carrying a water supply pipe were closed from one end, and the other end was connected to water source by two polyethylene (PE) tubes with a diameter of 18 mm by thread adapter (18 mm × 19 mm male “V”). The water source is generally a water pump, fertilizer apparatus and hydraulic equipment as a pressure gauge, flow meter, and a pressure regulator. The supply pipe includes eight saddles (63 mm × 12.7 mm female) at spacing of 50 cm, each saddle connected to one end of a vertically oriented drop line assemblies by tavlit push fit elbow male thread (16 mm × 12.7 mm male). The other end of the drop line was connected to manual flush valve of 16 mm. Each valve was connected to the upper end of the drip tube of 16 mm, and the lower end was closed by line end of 16 mm. PCJ online drippers were installed on the lower end of the drip tube, which was spaced above the ground.

Under this design, the wetting front advance in three directions, horizontal (H), vertical (V), and diagonal (D), is determined by drip tube discharge rate or system speed. The following equation can be used to compute the wetting front advance in three directions in loamy sand soil [15].

$$\alpha = 76.146 q_{dt}^{0.127} \quad (3)$$



Fig. 6 First use of linear mobile drip irrigation on a pea field in Egypt in 2016. Photograph was taken in December 2015 in the research field of Irrigation Systems Engineering Department, Faculty of Agricultural Engineering, Al-Azhar University, Nasr City, Cairo, Egypt [15]

$$\alpha = 42.859 S^{0.127} \quad (4)$$

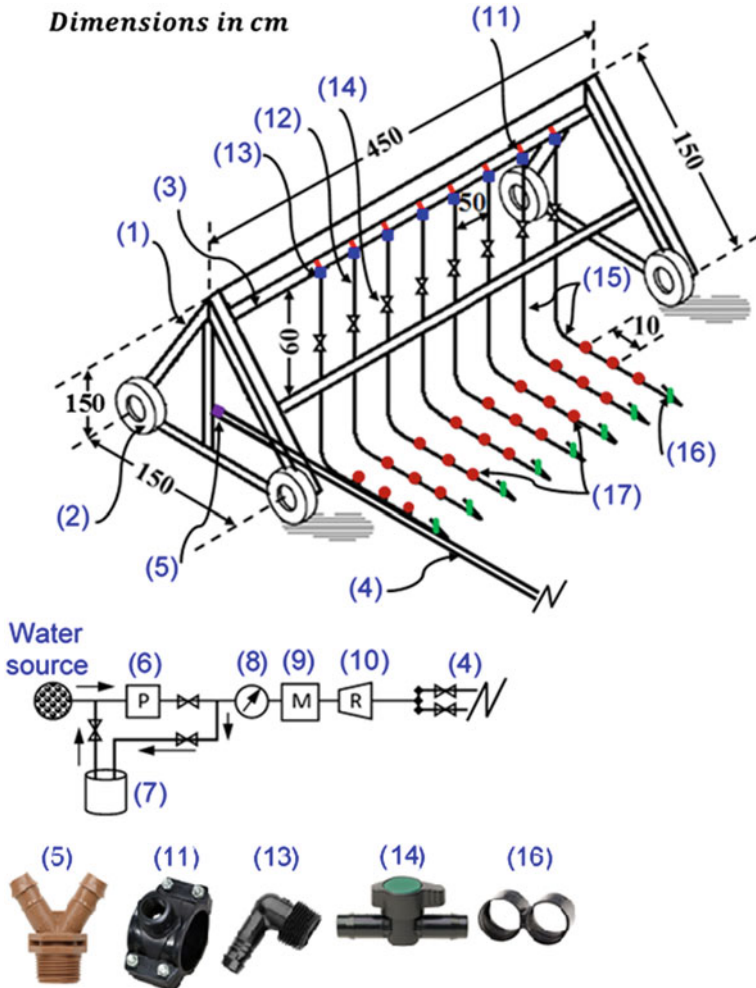
where α is the wetting front advance in any direction H , V , and D (m), q_{dt} is the discharge rate of drip tube (m^3/h), and S is the linear mobile drip irrigation system speed (m/h).

Generally, the mobile drip irrigation system (MDIS) consists of polyethylene (PE) drip line pulled through the field by the linear move irrigation system. As the drip lines are pulled behind the system, the integrated emitters deliver a uniform water pattern across the full length of the irrigated area. Because the drip lines deliver water directly to the soil surface, evaporation and wind drift are virtually eliminated, allowing more water to reach the soil surface and deeper percolation to the plant's root zone. <https://www.businesswire.com/news/-home/20150324006412/en/Netafim-USA-Names-Teete>.

3.5.1 Advantages of Mobile Drip Irrigation System

Mobile drip irrigation system provides certain advantages over other move systems as follows [11, 13, 15]:

- Increases yield.
- Saving water 10–20% compared with center pivot sprinklers.
- Used on either tall or short crops.
- No water losses due to wind drift and evaporation.
- Eliminates wheel track issues.



(1) Tower. (2) Driven wheel (175/70R13 82H). (3) Water supply pipe (UPVC 63 mm). (4) Two PE tubes 18 mm. (5) Thread adapter (18 mm x 19 mm male "V"). (6) Water pump. (7) Fertilizer apparatus. (8) Pressure gauge. (9) Flow meter. (10) Pressure regulator. (11) Saddles (63mm x 12.7 mm female). (12) Vertically oriented drop line assemblies. (13) Tavlit push fit elbow male thread (16 mm x 12.7 mm male). (14) Manual flush valve (16 mm). (15) Drip tube (16 mm). (16) Line end (16 mm). (17) PCJ on-line drippers.

Fig. 7 Components of linear mobile drip irrigation system (MDIS) as designed and constructed in Egypt 2016 [15]

- High irrigation efficiency.
- Flexibility of movement.
- Low operating pressure.
- Low capital requirements.
- Low labor requirements.

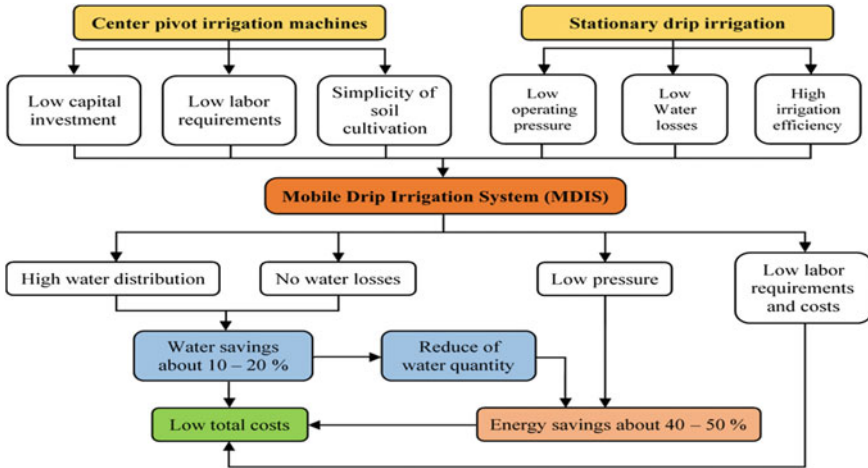


Fig. 8 Water and energy savings and the advantages of the MDIS [11]

- Soil cultivation under MDIS machines is easy.
- Soil stays moist without crusting, while soil compaction is reduced or eliminated.

Figure 8 illustrates the possibility of saving water and energy as well as the advantages of the mobile drip irrigation system [11].

The disadvantages of MDIS are [13]:

- Complex mechanical and electrical system.
- The MDIS (or other similar irrigation systems) represents a sizable capital investment.
- The system follows a straight line and does not correct for unequally spaced rows.

3.6 Ultra-low Drip Irrigation (ULDI) System

Ultra-low drip irrigation (ULDI) is a new aspect of micro-irrigation that has been researched in the past half-decade. Known as minute or ultra-low rate irrigation system or micro-drip irrigation, this new idea involves applying water at a rate close to that of plant water uptake, even lower than the natural soil infiltration rate. This process is accomplished by using spatters or pulsating drippers [16–19].

ULDI system has been developed that provides emitter discharge rates lower than 0.5 L/h [17]. ULDI system is able to apply water similar to or even lower than the soil water intake capacity. The ULDI system does apply 0.5 mm/h or even only a quarter of a millimeter per hour. Such an extremely low application rate will fit most soil water intake capacity. This low water application rate makes it possible to irrigate continuously during peak days around the clock [17–19].

In Egypt, ultra-low drip irrigation (ULDI) system was designed, built, and tested on squash crop for the first time in 2012 by Fayed [20], in research field of Water and Irrigation Systems Engineering Department, Faculty of Agricultural Engineering, Al-Azhar University, Nasr City, Cairo, Egypt. The system used emitters of 0.5 and 0.25 L/h (Fig. 9) under low pressure of 200 kPa.

Under ULDI system, field observations seem to indicate that there is no saturated zone and that the wetted soil volume is greater compared with that for conventional emitter discharges. Also, the moisture content in soil profile under ultra-low emitter point is always around the soil field capacity conditions [19].

The following equation can be used to compute the wetting front advance in three directions, horizontal (H), vertical (V), and diagonal (D) under ULDI system in sandy and clayey soil [20].

$$H = 11.54 t^{0.369} \cdot K^{0.053} \cdot q^{0.316} \quad (5)$$

$$V = 13.63 t^{0.410} \cdot K^{0.115} \cdot q^{0.295} \quad (6)$$

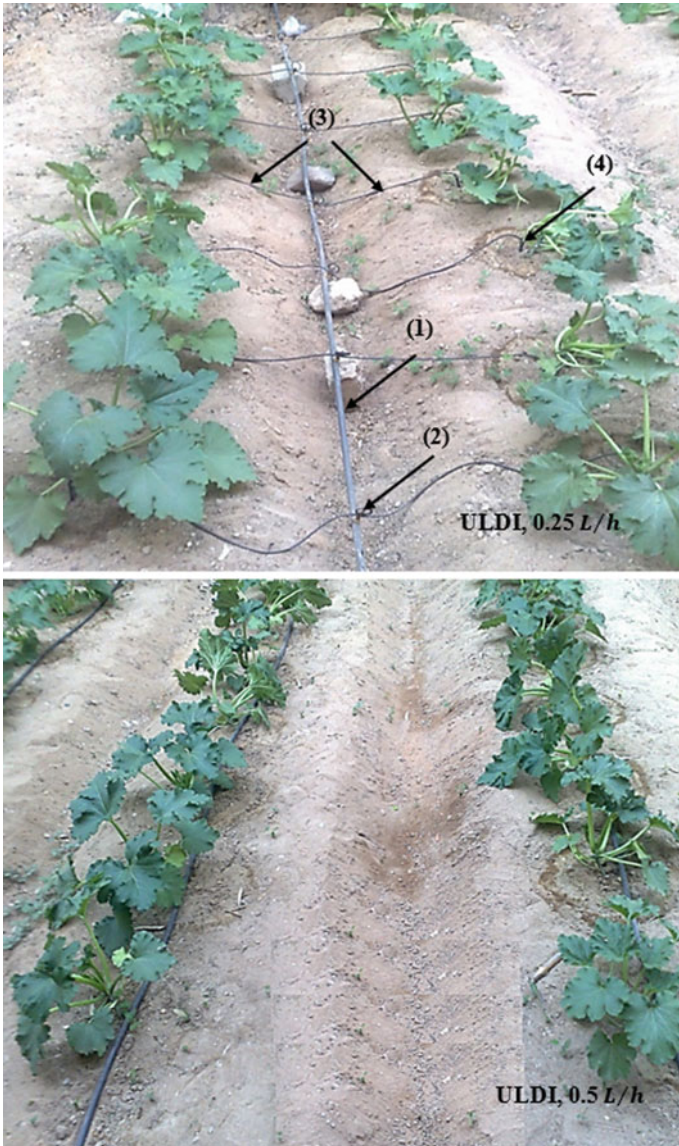
$$D = 13.45 t^{0.396} \cdot K^{0.095} \cdot q^{0.302} \quad (7)$$

where H , V , and D are the wetting front advances in horizontal, vertical, and diagonal, respectively (cm), t is the time of water application (h), K is the hydraulic conductivity of soil (cm/h), and q is the ultra-low emitter discharge rate (L/h).

3.6.1 Advantages of Ultra-low Drip Irrigation (ULDI) System

The advantages of ULDI system can be summarized as follows [16]:

1. Optimum growth conditions due to the ability to maintain optimum balance of air, water, and nutrients in the soil.
2. Better utilization of available space. Plant density can be increased.
3. Quicker turnaround of plant materials reducing growth cycles.
4. Higher yields.
5. Minimize leaching of nutrients that occur with excess water flow.
6. The ultra-low rate system is much cheaper than the common micro-irrigation systems, and smaller polyvinyl chloride (PVC) tube size reduced horsepower requirements.
7. No runoff on heavy soil.
8. No water loss through the root zone on very sandy soil.
9. Water and fertilizer saving up to 40–50%.
10. Better quality.
11. Water could be applied efficiently on shallow soils in hilly areas.



(1) Feeder lateral 16 mm. (2) On-line, pressure-compensated dripper 0.5 L/h (use with flat 2 or 4-way manifold). (3) Micro-tube 6 mm. (4) Angle arrow dripper.

Fig. 9 First use of ultra-low drip irrigation on a squash field in Egypt in 2012. Photographs were taken in June 2011 in the research field of Irrigation Systems Engineering Department, Faculty of Agricultural Engineering, Al-Azhar University, Nasr City, Cairo, Egypt [15]

4 Components of Drip Irrigation System

Drip irrigation system network has several components as shown in Fig. 10 [21]. Drip irrigation system is made up of many additional components. These components have to be compatible with each other, with the crop demands, and with the characteristics of the field to be irrigated.

The components are classified into six principal categories [1]:

1. Water source and pumping unit: A pumping system from an on-surface or underground source or a connection to public, commercial, or cooperative supply network.
2. Delivery system: Mainline, sub-mains, and manifolds (feeder pipelines).
3. Drip laterals (irrigating pipelines): Before it is discharged into the field through point source emitters, bubblers, or micro-sprinklers.
4. Control accessories: Valves, water meters, pressure gauges, flow regulators, automation devices, backflow preventers, vacuum and air release valves, etc.
5. Filtration system: Filters are sometimes omitted in the bubbler and spray sprinkler systems.
6. Chemical equipment: Drip systems may or may not include chemical injection equipment for the injection of plant nutrients and water treatment agents.

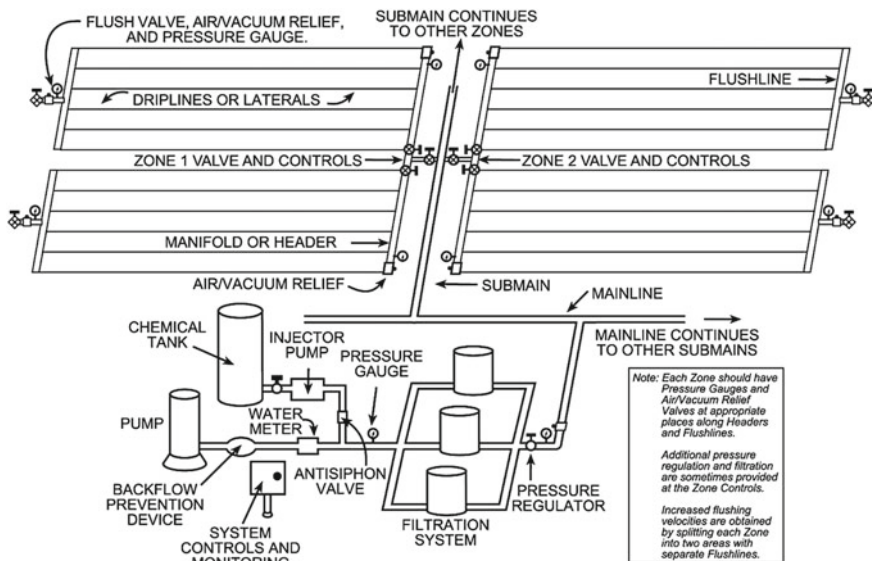


Fig. 10 Components of a drip irrigation system [21]. Credit Kansas State University

5 Design of Drip Irrigation System

5.1 General Steps for Design

When designing a drip irrigation system for a land area, it is necessary to obtain some important information that must be known to the designer. The information is required to design a drip irrigation system that can be classified as follows:

- **Climate data:** such as temperature, wind speed, rainfall distribution and its quantity. These data are required to calculate the evaporation of the plant.
- **Soil properties:** such as soil type, construction, porosity, soil density, field capacity, permanent wilting point, salinity ratio, leaching properties, and nutrients.
- **Plant properties:** type of yield, root depth, crop coefficient, and vegetative area.
- **Field data:** field form, area, drainage channels, and obstacles, etc.
- **Water source:** location, discharge rate, and water quality.
- **Economic information:** It includes the cost of equipment, energy cost, operation, labor, maintenance, and expected return.
- **Hardware and materials needed for design:** (These devices include pipes, valves, controllers, filters, fertilization vessels, meters, etc.) the necessary information about these devices such as performance curves, manufacturing different coefficients, etc.

5.2 Elements that Are Calculated When Designing Drip Irrigation System

The complete design of the drip irrigation system includes the following:

5.2.1 Calculate Maximum Net Depth of Each Irrigation Application (d_n)

It can be calculated from the following equation [22]:

$$d_n = AW \times D_s \times P_w \times \text{dep} \quad (8)$$

The available water (AW) is given by the following equation [6]:

$$AW = (\theta_{F.C} - \theta_{P.W.P}) \times \gamma_b \times 1000 \quad (9)$$

where d_n is the maximum net depth of each irrigation application in (mm), AW is available water in (mm/m), D_s is the soil depth to be considered in (m), P_w is the wetted area as a percent of the total area as a fraction, dep is the portion of available

moisture depletion allowed or desired, $\theta_{F,C}$ is soil moisture content on a weight basis at field capacity as a fraction, $\theta_{P,W,P}$ is soil moisture content on a weight basis at permanent wilting point as a fraction, and γ_b is the relative density of soil in (g/cm^3).

The ratio P_w depends on the type of plant and the distance between plants, either the distance between emitters on the line (S_e) or the distance between lines (S_1), depending on the type of planning used in the drip irrigation network.

In case of single straight lateral pattern, values of P_w are obtained from tables directly at the planting distances. In case of double straight lateral pattern, value of P_w is calculated from the following equation [22]:

$$P_w = \frac{(P_{w1}S_1) + (P_{w2}S_2)}{S_r} \quad (10)$$

where P_{w1} is taken from Table 1 for distance S_1 , S_1 is the narrow spacing between pairs of laterals (m), P_{w2} is taken from Table 1 for distance S_2 , S_2 is the wider distance between the laterals which is equal to $(S_r - S_1)$ (m), and S_r is the distance between tree rows (m).

In case of zigzag or pigtail pattern, value of P_w is calculated from the following equation [22]:

$$P_w = \frac{100 \times n \times S_{ep} \times S_w}{S_t \times S_r} \quad (11)$$

where n is the number of emission points per tree, S_{ep} is the distance between emission points (m), S_w is the width of the wetted strip which is the S_1 value taken from Table 1 which would give $P = 100\%$ for the given emitter discharge and soil (m), S_t is the distance between trees in the rows (m), and S_r is the distance between tree rows (m).

5.2.2 Calculate the Number of Emitters per Tree or Plant (N_e)

The number of emitters per tree or plant varies according to patterns of lateral as follows:

In case of single straight lateral pattern for each row of trees, the number of emitters per tree or plant can be calculated from the following equation [6, 22]:

$$N_e = \frac{k \times P_w \times S_t \times S_r}{D_w \times S_1} \quad (12)$$

where N_e is the number of emitters per tree or plant, k is constant equal to 100, P_w is the wetted area as a percent of the total area (%), S_t is the distance between trees or plants in the row (m), S_r is the distance between tree rows or plant rows (m), D_w is the maximum diameter of wetted circle formed by a single point source emission device (cm), and S_1 is the distance between emitter lines (cm).

Table 1 Percentage of soil wetted various discharge rates and spacing for a single row of uniformly spaced emission points in straight line applying 40 mm of water per cycle over the wetted area [22]

Effective spacing between laterals, S_1 (m) ^a	Emission point discharge (L/h) ^b														
	Less than 1.5			2			4			8			More than 12		
	C	M	F	C	M	F	C	M	F	C	M	F	C	M	F
0.2	0.5	0.9	0.3	0.7	1.0	1.3	1.0	1.3	1.0	1.3	1.7	1.3	1.6	2.0	
Recommended spacing of emission points along the lateral for coarse, medium, and fine textured soils— S_e (m) ^c															
Percentage of soil wetted ^d															
0.8	38	88	100	50	100	100	100	100	100	100	100	100	100	100	100
1.0	33	70	100	40	80	100	100	100	100	100	100	100	100	100	100
1.2	25	58	92	33	67	100	67	100	100	100	100	100	100	100	100
1.5	20	47	73	26	53	80	53	80	100	80	100	100	100	100	100
2.0	15	35	55	20	40	60	40	60	80	60	80	100	80	100	100
2.5	12	28	44	16	32	48	32	48	64	48	64	80	64	80	100
3.0	10	23	37	13	26	40	26	40	53	40	53	67	53	67	80
3.5	9	20	31	11	23	34	23	34	46	34	46	57	46	57	68
4.0	8	18	28	10	20	30	20	30	40	30	40	50	40	50	60
4.5	7	16	24	9	18	26	18	26	36	26	36	44	36	44	53

(continued)

Table 1 (continued)

	Emission point discharge (L/h) ^b															
	Less than 1.5		2		4		8		More than 12							
	Recommended spacing of emission points along the lateral for coarse, medium, and fine textured soils—S _e (m) ^c															
	C	M	F	C	M	F	C	M	F	C	M	F	C	M	F	
0.2	0.5	0.9	0.3	0.7	1.0	0.6	1.0	1.3	1.0	1.3	1.7	1.3	1.7	1.3	1.6	2.0
Percentage of soil wetted ^d																
5.0	6	14	22	8	16	24	16	24	32	24	32	40	32	40	48	48
6.0	5	12	18	7	14	20	14	20	27	20	27	34	27	34	34	40

Courtesy Rain Bird Corporation

^aWhere double laterals (or laterals having multi-exit emitters) are used in orchards and enter with the average lateral spacing as S_l, provided the spacing between any two laterals (or rows of emission points) is equal to or greater than an S_l value which would give P %

^bWhen irrigation is applied in relatively short pulses, the horizontal spread of the wetted zone is less than for heavier applications. Therefore, the table should be entered with an effective emission point discharge of approximately half the instantaneous discharge. In soils with hardpans, clay or sand lenses, or other stratifications which enhance the horizontal spread of moisture, the table may be entered with up to double the installation rate for regular application (or for the instantaneous rate for short pauses)

^cThe texture of the soil is designated by C, coarse; M, medium; and F, fine. The emission point spacing is equal to approximately 80% of the largest diameter of the wetted area of the soil underlying the point (closer spacings on the lateral do not affect the percentage area wetted)

^dThe percentage of soil wetted is based on the area of the horizontal section approximately 0.30 m beneath the soil surface. In wide-spaced tree crops, caution should be exercised where less than 1/3 of the soil volume will be wetted in low rainfall areas or 1/5 in high rainfall areas. In close-spaced crops, most of the soil volume may need to be wetted to assure a sufficient water supply to each plant

In the other patterns, double laterals for each row of trees, multi-exit emitter hose to distribute water, zigzag single lateral for each row of trees and pigtail with emitters connected to single lateral, and the number of emitters per tree or plant can be calculated from the following equation [2]:

$$N_e = \frac{2k \times P_w \times S_t \times S_r}{S_l(S_l + D_w)} \tag{13}$$

In the double lateral pattern for each row of trees, the distance between double laterals should be equal to the value of D_w where the largest wet area can be obtained. In the case of zigzag, pigtail, and multi-exit patterns, the distance between emitters must be equal to D_w value in each direction.

In case of micro-sprinklers, the number of it can be calculated from the following equation [2]:

$$N_e = \frac{P_w \times S_t \times S_r}{100(A_s + \frac{D_w + P_s}{2k})} \tag{14}$$

where A_s is the irrigated area by micro-sprinkler (m^2) and P_s is circumference of the wetted circle (cm). In the previous equation, D_w can be calculated as follows [2]:

$$S_e = D_T + \frac{D_w}{2k} \tag{15}$$

where D_T is the ejaculation distance of the micro-sprinkler (m) and S_e is the distance between emitters on the line (m).

5.2.3 Calculate the Number of Operating Stations (or Units) into Which a Field Is Divided (N)

Naturally, it is difficult to irrigate the total area at the same time, so the total area should be divided into a number of operating stations that will be irrigated alternately during the irrigation period. The number of operating stations (or units) into which a field is divided is calculated from the following equation [2, 6, 22]:

$$N \leq \frac{H_a \times q_t}{S_e \times S_l} \times \frac{0.90 \text{ EU}}{\text{ET}_O} \tag{16}$$

or

$$N \leq \frac{H_a \times F}{h} \tag{17}$$

where N is the number of operating stations (or units) into which a field is divided, H_a is actual daily operating hours for pump and motor (it is ranging from 12 to

15 h/day), and q_t is total discharge rate for single tree (L/h). If each tree is irrigated by three emitters, q_t is equal to $3 \times$ discharge rate of single emitter. S_1 is the distance between lines, EU is the emission uniformity as a fraction, ET_O is the transpiration rate of the crop (mm/day), F is the irrigation interval (day), and h is total time of operation for each operational unit during each irrigation cycle (h).

5.2.4 Calculate the Total Discharge Rate of Drip Irrigation Network (Q)

The total discharge rate (system capacity) of the drip irrigation system network can be calculated from the following equation [2, 22]:

$$Q \text{ (m}^3\text{/h)} = \frac{A \times F \times ET_O}{N \times h \times 0.90 \text{ EU}} \times 10^{-3} \quad (18)$$

or

$$Q \text{ (m}^3\text{/h)} = \frac{A \times q_t}{N \times S_e \times S_1} \times 10^{-3} \quad (19)$$

or

$$Q \text{ (m}^3\text{/h)} = \frac{A \times d_g}{N \times h} \times 10^{-3} \quad (20)$$

Also, the total discharge rate of drip irrigation network can be calculated by another method in $\text{m}^3\text{/day}$ as follows [2]:

$$Q \text{ (m}^3\text{/day)} = \frac{A \times F \times H_a \times ET_O}{N \times h \times 0.90 \text{ EU}} \times 10^{-3} \quad (21)$$

where Q is total discharge rate of drip irrigation network ($\text{m}^3\text{/h}$), A is the total area to be irrigated (m^2), and d_g is the gross depth of each irrigation application (mm).

The gross depth of each irrigation application can be calculated directly by the following equation [2, 6, 22]:

$$d_g = \frac{d_n}{E_a} = \frac{F \times ET_O}{E_a} \quad (22)$$

where E_a is the efficiency of irrigation (efficiency of applying water) by a drip irrigation system as a fraction.

The irrigation efficiency (E_a) is expressed by the following equation [2, 22]:

$$E_a = K_s \times \text{EU} \quad (23)$$

where K_s is a coefficient less than one and expresses deep percolation losses in which [2, 6]:

$$K_s = \frac{\text{Average water stored in root volume}}{\text{Average water applied}} \tag{24}$$

Since it is difficult to calculate the value of K_s , it is estimated based on soil type as follows [23]:

Coarse sand or light topsoil with	
Gravel subsoil	$K_s = 0.87$
Sand	$K_s = 0.91$
Silt	$K_s = 0.95$
Loam and clay	$K_s = 1.00$

5.2.5 Calculate the Time of Operation for Each Operational Unit During Each Irrigation Cycle (h)

The time of operation for one section of total area sections can be calculated from the following equation [2, 6, 22]:

$$h = \frac{S_e \times S_l \times d_n}{q_t} \tag{25}$$

5.2.6 Calculate the Irrigation Requirement Under Drip Irrigation System (I.R)

The irrigation requirement for trees or vegetable crops under drip irrigation system can be calculated from the following equation [2]:

$$I.R = \frac{ET_o \times K_c \times K_r \times S_e \times S_l}{E_a \times EU (1 - LR)} \tag{26}$$

where I.R is the irrigation requirement per one tree or one plant (L/day), K_c is crop coefficient, K_r is the appropriate ground cover reduction factor, and LR is the amount of water required for leaching of salt (a number less than one).

The crop coefficient (K_c) is taken from FAO’s tables [24]. The amount of water required for the leaching of salts (LR) can be calculated from the following equation [2]:

$$LR = \frac{EC_i}{EC_d} \quad (27)$$

where EC_i is an electrical conductivity of irrigation water (dS/m or mmhos/cm) and EC_d is an electrical conductivity of the saturated soil extract (dS/m or mmhos/cm).

The appropriate ground cover (GC) reduction factor is a number less than one and can be calculated from the following equations [2, 23]:

- **Keller and Karmeli equation:**

$$K_r = \frac{GC}{0.85} \quad (28)$$

- **Freeman and Garzoli equation:**

$$K_r = 0.50 (GC + 1) \quad (29)$$

- **Decroix and CTG REF equation:**

$$K_r = 0.10 + GC \quad (30)$$

FAO 1984 provides the reduction factors suggested by various researchers in order to account for the reduction in evapotranspiration as shown in Table 2 [23].

Table 2 Values of K_r suggested by different authors [23]

GC (%)	Crop factor K_r according to		
	Keller and Karmeli	Freeman and Garzoli	Decroix CTG REF
10	0.12	0.10	0.20
20	0.24	0.20	0.30
30	0.35	0.30	0.40
40	0.47	0.40	0.50
50	0.49	0.75	0.60
60	0.70	0.80	0.70
70	0.82	0.85	0.80
80	0.94	0.90	0.90
90	1.00	0.95	1.00
100	1.00	1.00	1.00

6 Evaluation of Drip Irrigation System

Evaluation of drip irrigation system includes evaluation of the following elements:

1. The gross depth of each irrigation application (mm).
2. The irrigation requirement per tree or plant (L/day).
3. Are the hours of daily operation given the necessary irrigation requirements? Especially when the maximum daily water requirement under Egyptian conditions at the age of the tree that needs the maximum water requirement.
4. Distribution of moisture in the soil profile in three directions as follows:
 - In horizontal direction between trees or plants along one row.
 - In vertical direction (horizontal) between rows.
 - In the depth of both previous directions.
5. Distribution of salts in the soil profile at the same previous directions.
6. Efficiency of the filters.
7. Efficiency of the emitters and their suitability for soil type and plant type.
8. Water losses.
9. Network efficiency in general.
10. Economics and costs of drip irrigation network.

6.1 *Experimental Evaluation of Drip Irrigation Network*

The drip irrigation network to be evaluated for a specific period of 3–4 h is operated, and the following elements are measured [2].

6.1.1 **Watching Water Pressure (on Pressure Meter) Before and After the Filter Unit**

It is normal to have pressure before the filters greater than after, but at 50 kPa, and if the difference is more, it means there are deposits in the filters and therefore filters should be washed if the reverse washing is done manually. If reverse washing is done automatically, it is not necessary to note filters, only to see efficiency of the filters.

6.1.2 **Determination of the Net Depth of Each Irrigation Application (d_n)**

Previously, the net depth of each irrigation application (d_n) under drip irrigation system has already been calculated in Sect. 5.2.1.

6.1.3 Determination of the Irrigation Requirement (I.R)

Previously, irrigation requirement per tree or plant (I.R) under drip irrigation system has already been calculated as follows [2, 23]:

$$\text{I.R (L/day)} = \frac{\text{ET}_O \times K_c \times K_r \times S_e \times S_l}{E_a \times \text{EU}(1 - \text{LR})} \quad (31)$$

By operating the required hours according to the irrigation program, the amount of water added per tree or plant can be calculated as follows [2]:

$$\text{Water amount added per tree or plant (L/day)} = q_t \times H \quad (32)$$

6.1.4 Distribution of Moisture and Salts in Soil Profile

This is done by taking samples of different depths [(0–20), (20–30), (30–40), (40–60), and (60–80) cm] and may increase depending on soil type, depth of irrigation water, and age of plant. This is done for all the depths between the plants or trees on the row and between the rows, and then the results obtained are drawn in contour lines.

6.1.5 Emitter Evaluation

There are some very important parameters to evaluate the performance of emitters. These parameters are of emitter discharge (q), the emitter discharge exponent (x), the coefficient of variation of the discharge (C_v), emission uniformity (EU), emitter flow variation (q_{var}), and application efficiency (E_a). These parameters are described below:

1. Pressure–Discharge Relationship

In the design of drip irrigation systems, the relationship between emitter discharge and operating pressure is calculated based on the emitter flow function given by Keller and Karmeli [22, 25] as follows:

$$q_e = K_d \cdot h_d^x \quad (33)$$

where q_e is emitter discharge rate (L/h), K_d is constant of proportionality that characterizes each emitter, h_d is the operating pressure head at the emitter (m), and x is emitter discharge exponent that is characterized by the flow regime.

The discharge rate of several emitters (more than 20 emitters) must be measured along the drip line at different operating pressures. Then, the results are drawn to know the difference in the discharge rates. The average discharge rate of emitters for

each line is calculated to predict the moisture distribution which can result from this and the extent of differences in this moisture or salt distribution along the drip line.

2. Manufacturer’s Coefficient of Variation (C_v)

Manufacturer’s coefficient of variation of the discharge (C_v) is one of the significant parameters related to the uniformity and efficiency of the system. It could be obtained by taking a random sample of emitters and measuring the discharge rates at the same temperature and pressure. It can be calculated by using the following equation [23]:

$$C_v = \frac{Sd}{q_{avg}} \tag{34}$$

where C_v is manufacturer’s coefficient of variation, Sd is estimated standard deviation of the discharge rates of sampled set of emitters (L/h), and q_{avg} is the average discharge rates of sampled set of emitters (L/h).

The standard deviation values can be calculated in the same manner using the following equation [23, 26]:

$$Sd = \left(\frac{(q_1^2 + q_2^2 + \dots + q_n^2) - n(q_{avg})^2}{n - 1} \right)^{0.5} \tag{35}$$

where q_1, q_2, \dots, q_n is discharge rate of emitters tested (L/h) and n is the number of emission devices tested.

The coefficient of discharge variation values can be classified according to ASAE Standards [26] as shown in Table 3.

3. Emission Uniformity (EU)

In order to determine if the system is operating at acceptable efficiency, the uniformity of emission can be evaluated by the following equation [6, 22, 23, 26]:

$$EU = 100 \times \left(1.0 - \left[\frac{1.27}{\sqrt{n}} C_v \right] \right) \times \left(\frac{q_{min}}{q_{avg}} \right) \tag{36}$$

Table 3 Recommended classification of manufacturer’s coefficient variation (C_v) [26]

Emitter type	C_v range		Classification
Point source		<0.05	Excellent
	0.05	0.07	Average
	0.07	0.11	Marginal
	0.11	0.15	Poor
		>0.15	Unacceptable
Line source		<0.10	Good
	0.10	0.20	Average
		>0.20	Marginal to unacceptable

Table 4 Recommended ranges of design emission uniformity (EU) [26]

Emitter type	Spacing (m)	Topography	Slope (%)	EU range (%)
Point source on perennial crops	>4	Uniform steep or undulating	<2	90–95
			>2	85–90
Point source on perennial or semipermanent crops	<4	Uniform steep or undulating	<2	85–90
			>2	80–90
Line source on annual or perennial crops	All	Uniform steep or undulating	<2	80–90
			>2	70–85

where EU is the design emission uniformity (%), n is the number of emitters per plant, and q_{\min} is the minimum emitter discharge for minimum pressure in the sub-unit (L/h).

General criteria for EU values for systems which have been in operation for one or more seasons are: greater than 90%, excellent; between 80% and 90%, good; 70–80%, fair; and less than 70%, poor [27].

Table 4 shows range for EU values recommended by ASAE for use in Eq. 36 [26]. Economic considerations may dictate a higher or lower uniformity than those given in Table 4 [6].

4. Variation from Hydraulic Design (q_{var})

Flow variation within laterals occurs due to pressure head variations and manufacturing variations of the individual emitters. Both of these processes will be discussed and related as to how they can be used in the design process. Lateral emitter flow variation (q_{var}) was determined as the following equation given by Wu and Gitlin [28]:

$$q_{\text{var}} = \frac{q_{\text{max}} - q_{\text{min}}}{q_{\text{max}}} \times 100 \tag{37}$$

where q_{var} is lateral emitter flow variation (%), q_{max} is maximum emitter flow rate (L/h), and q_{min} is minimum emitter flow rate (L/h).

Wu and Gitlin [28] recommended the general criteria for emitter flow variation (q_{var}) values which are 10% or less is generally desirable, acceptable when between 10 and 20%, and unacceptable when greater than 20%.

5. Application Efficiency (E_a)

The efficiency of applying water by a drip irrigation system depends on the uniformity of application (EU). Application efficiency (E_a) can be calculated by using the following equation [2, 22, 24]:

$$E_a = K_s \times \text{EU} \tag{38}$$

6.1.6 Water Losses and Network Efficiency

The drip irrigation network should be continuously observed during operation, especially the pressure meters and the emitters to avoid any decrease in the operating pressure or the discharge rate of the emitters. If happened, it means a leakage in one of the main or sub-main lines exist. The leak position should be detected and repaired immediately [2].

The various components of a drip irrigation system network require different preventative and operational maintenance procedures to ensure proper system performance and extend the life of the component. These procedures that can be implemented to roughly evaluate performance are as follows [29]:

The first step is to check the hourly flow rate at the main flow meter and compare it with the designed flow rate [design flow rate (L/h) = number of emitters × emitter nominal flow rate (L/h)].

Second step is the pressure gauges that are installed in the plot have to be checked. The measured values have to be compared to the designed pressure for each set. The pressure difference between inlet and outlet and dirt accumulation in filters have to be checked as well.

Also, a periodic visual inspection of the status of the media could help assess drip irrigation network effectiveness and indicate if the backwashing schedule needs to be adjusted, or perhaps chlorination is needed; due to excess biomass growth regularly scheduled maintenance operations, such as the monthly flushing of all laterals, can prevent accumulation of fines and the potential for irreversible emitter plugging. It is advisable to follow the instructions provided by the suppliers of all the components of the drip irrigation system with care [30].

6.1.7 Economics and Costs of Drip Irrigation Network

The cost of the drip irrigation network is calculated after the appropriate design has been made and then the total costs are calculated. Annualized operating costs can be estimated by calculating fixed and variable annualized costs [2].

7 Summary

Drip or trickle irrigation is the most efficient method of irrigating. The drip irrigation system works by applying water slowly, directly, and at frequent intervals to the soil through mechanical devices called emitters or drippers, localized at selected points along the water delivery line. Also, the drip irrigation can apply the fertilizers and pesticides with irrigation water. The different types of drip irrigation comprise: surface, subsurface, bubbler, micro-sprinkler, mobile drip irrigation, and ultra-low drip irrigation. All drip irrigation systems consist of a pumping unit, fertigation unit, filtration unit, a control head, main and sub-main pipes, laterals, and emitters.

The complete design of the drip irrigation system includes calculation of: the maximum net depth of each irrigation application (d_n), the number of emitters per tree or plant (N_e), the number of operating stations (or units) into which a field is divided (N), the total discharge rate of drip irrigation network (Q), the time of operation for each operational unit during each irrigation cycle (h), and the irrigation requirement under drip irrigation system (I.R).

The evaluation of drip irrigation system includes evaluation of: watching water pressure (on pressure meter) before and after the filter unit, determination of the net depth of each irrigation application (d_n), determination of the irrigation requirement (I.R), distribution of moisture and salts in soil profile, emitter evaluation, water losses and network efficiency and economics and costs of drip irrigation network.

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