GOVERNMENT OF THE PUNJAB
Agriculture Department

TECHNICAL BRIEF
13

MAXIMIZING WATER PRODUCTIVITY *THROUGH* EXACT TIMING AND AMOUNTING OF IRRIGATION

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BACKGROUND

Soil moisture is the most critical and highly variable component of the crop root zone environment. It directly affects the plant growth through its controlling effect on availability and uptake of almost all nutrients. Moreover, water being constituting virtually 90 percent of plant body, plays following multifaceted roles in its growth.

- Dissolves plant food available in the soil and transports it throughout the plant
- Drives photosynthesis process by enabling CO_2 uptake from the atmosphere
- Acts as reactant for various bio-chemical processes like hydrolysis
- Helps maintain temperature in soil and plant canopy
- Serves as solvent for mineral absorption in plant cells
- Provides turgor pressure required for cell expansion and maintenance of its shape

Adequate maintenance of soil moisture according to requirements of various stages of plant growth is, therefore, the most important single factor in crop production. Application of too much water not only causes its wastage but also that of other nutrients, energy, and labor. Furthermore, excess water in the root zone reduces soil aeration retarding plant growth. Likewise, under irrigation stresses the crop by constraining availability of water as well as non-water nutrients. As such, under or over application of water, both lead to reduced crop yields and poor quality of produce. The water shortage at any stage of plant growth retards its development and hampers photosynthesis process.

The farmers in Pakistan irrigate crops solely based on visual observations of soil and crop appearance and/ or on availability of water at their rotational turn of canal supply. Uncontrolled surface flooding is the only method of water application, which results in over irrigation during initial crop growth stage and under irrigation at its maturity/fruit development. The ultimate success of irrigation operation is, therefore, largely dependent on the water management skills of the irrigator.

The technological developments have significantly advanced over the past decades enabling efficient use of irrigation water to increase crop yields and improve quality of produce. Adoption of scientific techniques and technologies of irrigation scheduling can bring a breakthrough in maximizing water productivity in crop production.

Over Irrigation	Under Irrigation
Restricts root zone aeration and stresses plant growth	Restricts crop growth by constraining water availability
Leaches soil nutrients	Adversely affects produce quality
Encourages root diseases	Weakens plants
Retards root development	Reduces crop yield
Wastes energy	
Lowers produce quality	

IRRIGATION SCHEDULING

Irrigation scheduling is the accurate determination of "*WHEN and HOW MUCH water to be applied to a field*" thereby providing exact amount of water to crop at the right time. It is an important tool for optimizing the plant growth by ensuring adequate water availability. The timing of an irrigation event (*WHEN*) depends on plant need and soil water condition whereas "*HOW MUCH*" is contingent upon soil's water holding capacity, crop rooting depth, soil moisture depletion level, and planned irrigation interval. The irrigator should have complete control over irrigation operation e.g. flow rate, water application duration, irrigation frequency etc. for maximizing water use efficiency and ultimately attaining higher crop production.

ADVANTAGES

The importance of irrigation scheduling has long been recognized and a wide range of scientific and practical tools have been developed to help farmers in applying water to crops more accurately because of its following advantages.

- Minimizes the crop water stress thereby increases crop output.
- Reduces cost of irrigation by making maximum use of soil moisture storage.
- Decreases labor through optimizing irrigation duration.
- Curtails fertilizer costs by controlling surface runoff and deep percolation.
- Reduces waterlogging thus decreases drainage requirements.
- Lessens root zone salinity problems.
- Controls excessive vegetative growth.
- Increases net returns from farming by increasing crop yield and improving quality of produce.

SOIL-WATER-PLANT RELATIONSHIP

In order to scientifically schedule irrigation, it is required to understand basic concepts of soil-water-plant relationship. The water in the root zone is taken up by the plants though roots. The rate of entry of water into soil and its retention, movement, and availability to plant roots are all physical phenomena. Hence, it is important to understand soil properties for efficient management of irrigated agriculture.

The Soil

Soil is composed of minerals, organic matter, air, and water. It supplies plant nutrients, provides mechanical support to plants, and stores water. Its mineral fraction consists of various particle sizes including sand, silt, clay, and rock. There are spaces between the particles known as soil pores. The texture of soil is the relative proportion of various sizes of mineral particles, which differs widely in size as given in Table-1. The availability of water, air, minerals & organic matter before and after flooding and under drip irrigation is shown in Figure-1.

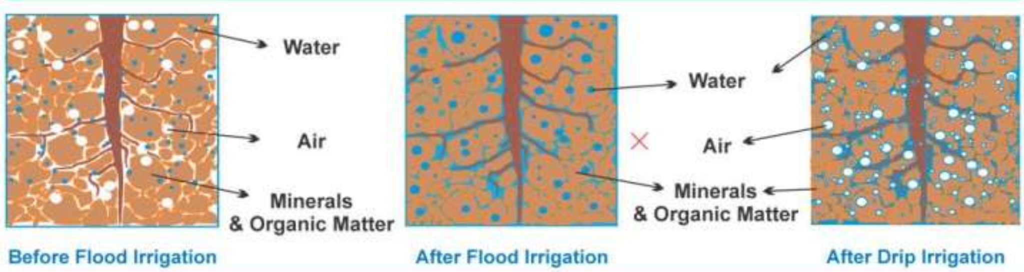


Figure 1: Composition of soil

Table1: Classification of mineral particles in the soil

Particle	Size Range (mm)	Distinguishable with Naked Eye
Gravel	More than 1	Easy
Sand	1-0.5	Easy
Silt	0.5 to 0.002	Difficult
Clay	Less than 0.002	Impossible

Source: OFWM Field Manual, Volume VI, Irrigation Agronomy, Federal Water Management Cell

Scheduling irrigation maximizes profits

Soil structure is the arrangements of soil aggregates (sand, silt, clay, organic matter) into porous compounds. The basic types of aggregate arrangements are granular, blocky, prismatic, and massive as shown in Figure-2.

Table2: Common terms to describe soil

Expressions Used by Farmers	Technical Term
Light	Sandy Coarse
Medium	Loamy Medium
Heavy	Clay Fine

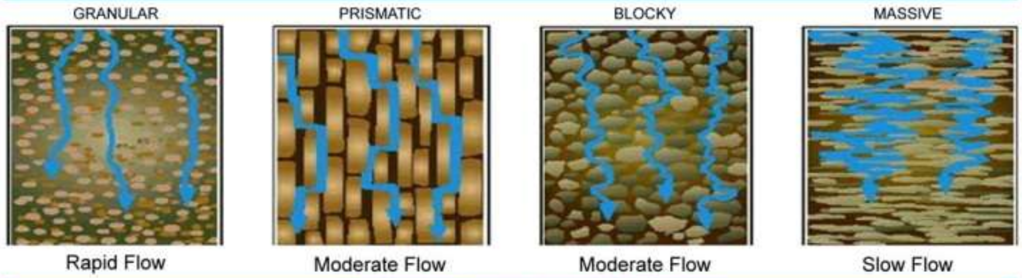


Figure 2: Examples of soil structure

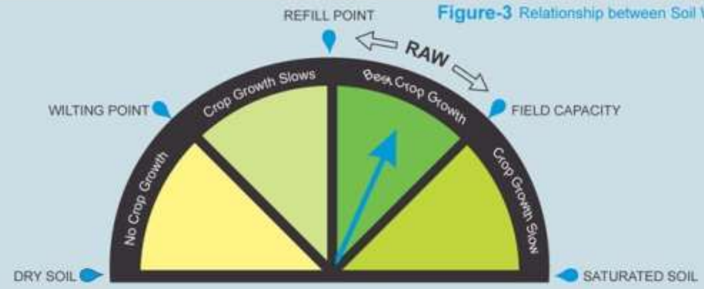
Soil Water

When soil is irrigated, water moves down through pores or openings between the particles. The velocity with which the water seeps into the soil is called the **infiltration rate** of soil. The water film, formed around each individual soil particle, is tightly held around soil particles. After filling of the root zone completely, the water film becomes so thick that surface tension can no longer resist the pull of gravity and the extra water moves downward the crop root zone, which is termed as **gravitational water (GW)**.There remains no air in the soil at this stage and soil is called in saturation condition.

A field does not usually remain saturated for long after irrigation and it takes only a few hours to drain away the water in sandy soils but the process in clay soils is completed in days. At attaining equilibrium between gravity and the evaporative forces, the evaporation process at soil surface pulls the water upward through capillary action while surface tension holds it around the soil particles. At this stage, the soil grasps the maximum amount of water available for plants against the pull of gravity that is called the **field capacity (FC)**.This moisture condition, for a well-drained soil, occurs one to three days after a thorough irrigation.

The soil moisture that the plant can extract for unrestricted growth is termed as **readily available water (RAW).** After consumption of the RAW, the moisture extraction becomes difficult for plants and more water is required to maintain the optimum growth, the soil at this stage is said to be at **refill (RF) point**. The drier the soil, the more water would be needed to bring it back to **FC**. Generally **RF** point is taken as 50 percent of available water, though strictly speaking it depends on crop growth. If field is not irrigated at RF point, the growth slows down and further dryness leads soil to **wilting point (WP).** Temporary wilting can occur in many crops on a hot windy day but the plants recover in cooler part of the day. A plant is permanently wilted when it will not recover from rewetting and the soil water contents at this stage is called as **permanent wilting point (PWP)**. There may be some water in soil, but too difficult for the roots to extract it, as the water is held with a suction force of about 15 atmospheres (-15 bar).

Figure-3 Relationship between Soil Water and Crop Stress



Source: Farm Note 543, Department of Agriculture and Food, Government of Western Australia (2012)

The wilting of plant depends on (a) rate of water used by plants; (b) the depth of the root zone; and (c) the water holding capacity of the soil. The water held by the soil between FC and PWP is termed as available water content or water holding capacity, which depends on texture and structure of the soil. A range of values of water holding capacity (WHC) for different types of soils is given in Table-3.

Table 3: Available water content of different soils

Soil Texture	Water Holding Capacity	
	Range (mm/m)	Average (mm/m)
Very coarse textured – very coarse sand	33-62	42
Coarse textured – coarse sand, fine sand, and loamy sands	62-104	83
Moderately coarse texture – sandy loams	104-45	125
Medium texture – very fine sandy loams, loams, and silt loams	125-192	167
Moderately fine texture – clay loams, silt & sandy clay loams	145-208	183
Fine texture – sandy clay, silty clay, and clays	133-208	192
Peats and mucks	167-250	208

Source: Jack Keller & Ron D. Bliesner

The water holding capacity is closely related to soil texture. For instance, sandy soils hold about less than 25 percent as much plant available water as a silt loam with an equivalent rooting depth. Figure-4 shows the relationship between FC, WP, and plant's available water for different soil textures.

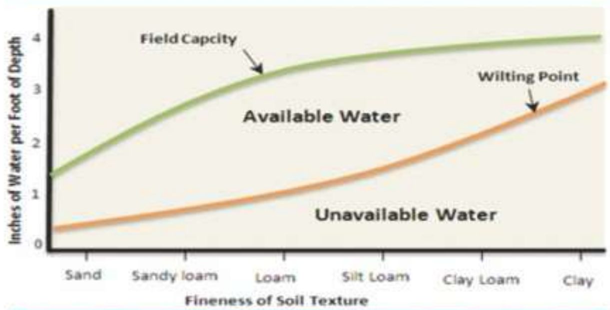
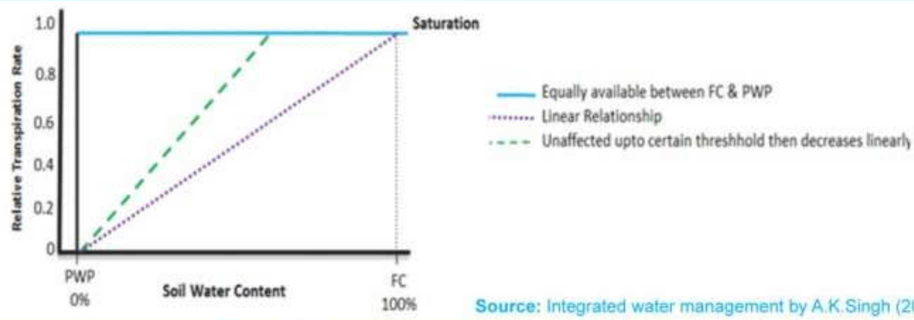


Figure 4: Effect of soil texture on available water for different soils

Soil Water Availability to Plants

There are three theories regarding ease of water withdrawal by the crop between *FC* and *WP*. One consideration is that the water remains uniformly available to the plant between these two extremes whereas second school of thought considers that its availability proportionally declines as quantity of the soil moisture content moves towards wilting point. There is a third group of scientists who postulates that water availability to plants remains unrestrictedly available up to a certain level between saturation level and WP and its further decline from this stage, water availability to plant is considerably restricted, which is actually the RF or time to irrigate (Figure-5).



Source: Integrated water management by A.K.Singh (2007)

Figure 5: Concepts of soil moisture availability

It is, however, established that best crop growth occurs when the soil moisture level remains within RAW range, whereas crop growth slows down above or below it (Figure-3).

Management Allowed Deficit (MAD) is another concept used in irrigation scheduling, which is the deficit allowed for management to start irrigation. This indicates that plant can uptake water in sufficient amounts, not only for its survival but also for normal growth. The MAD value, however, is a function of soil type and not much research has been done for this aspect. Scientifically MAD values should be more for clay soil and less for sandy soil.

Effective Root Zone of Crop

The effective root zone of a plant is the area where the main mass of its roots is found. Water below it is lost to deep percolation or is not instantly used by the plant. The distribution of roots and water use in the root zone by a crop is not uniform in depth. The rooting depth varies with the growth stage of crop. Over the course of the growing season, plants generally extract about 70 percent water from effective root zone (top half) than from the lower part. Rooting depths are often modified by soil compaction, stratification, and moisture conditions. The root development and percentage of moisture extraction from the active root zone in deep and uniform soil is shown in Figure 6.

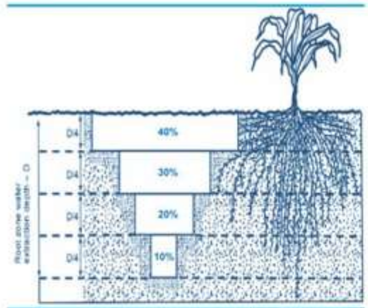


Figure 6:Root development in a deep and uniform soil

Crop Critical Growth Stages

There are critical stages in the plant growth period where optimum moisture level must be maintained for getting high yields. The critical period for annual crops mostly occurs during flowering and ripening stages i.e. in the later part of the season. Crops like paddy, sugarcane, potato, and banana are very sensitive to irrigation supplies, which means minor water shortages considerably reduce yield. The crops like millet and sorghum, on the other hand, are less sensitive to drought. For example; a farmer growing potatoes and wheat, when faces water shortages should give priority to irrigate potatoes because of its more sensitivity to irrigation deficiency. The sensitivity of major crops to water stress is given in Table-4.

Table 4: Sensitivity of various crops to water stress

Sensitivity			
Low	**Low - Medium**	**Medium - High**	**High**
Cotton Sorghum Millet Cassava Pigeon Pea	Wheat Sunflower Citrus Groundnut Soyabean	Maize Tomato Onion Peas Watermelon Pepper Beans Cabbage	Paddy Sugarcane Potato Green Vegetables Banana

Source: OFWM Field Manual, Volume VI, Irrigation Agronomy, Federal Water Management Cell

The length of entire growing season and each growth stage of crop are important for estimating crop water needs. The growth of an annual crop is usually divided into four stages.

- Initial establishment: from sowing to 10 percent ground cover
- Vegetative development: from 10 to 70 percent ground cover
- Fruit formation (mid-season): flowering and fruit setting (yield formation)
- Fruit ripening (late-season): maturity and harvest

The quantity of water needed to meet crop water requirements depend on crop type, growth stage, local climate, soil conditions, and irrigation interval. The critical period for commonly irrigated crops, their MAD, and root depths are given in Table-5.

Table5: Critical growth stages, rooting depth and MAD for different crops

Crop	Crop Critical Growth Stages	Root Zone Depth (m)	MAD (%)
Wheat	tillering, flowering, grain filling	0.9 - 1.5	50
Rice	flowering, head development, recovery period after transplanting	0.9 - 1.5	80-100
Cotton	flowering, ball formation	0.9 - 1.5	65
Sugarcane	tillering, stem elongation	0.9 - 1.5	50-70
Maize	flowering tasseling, silking, pollination), grain filling	0.9 - 1.5	50
Sunflower	flowering, seed development, vegetative period	0.5 - 1.0	60
Groundnut	flowering, yield formation	0.5 - 1.0	50
Soyabean	flowering, pod development, filling	0.5 - 1.0	50
Citrus	flowering, fruit setting	0.9 - 1.5	50
Mango	flowering and fruit set	2.0 - 2.5	50
Datepalm	flowering, fruit development	1.5 - 2.5	50
Ber	flowering, fruit development	3.0 - 4.0	60
Pomegranate	flowering, fruit development	2.0 - 3.0	50
Potato	stolon growth, tuber initiation	0.3 - 0.6	70
Tomato	transplanting, flowering, fruit filling	0.5 - 1.0	65
Chillies	before and after flowering	0.5 - 1.0	60
Onion	bulb enlargement	0.3 - 0.6	70
Peas	flowering seed filling	0.5 - 1.0	35
Turmeric	throughout growth period	0.4 - 0.5	50
Radish	throughout growth period	0.4 - 0.6	50
Cucumber	flowering, fruit development	0.3 - 0.4	50
Spinach	throughout growth period	0.4 - 0.6	65
Bringal	throughout growth period	0.7 - 1.3	60
Garlic	bulb formation	0.2 - 0.6	70
Cauliflower	seedling, head enlargement, ripening	0.3 - 0.7	65
Turnip	roots swelling until harvest	0.3 - 0.6	65
Gourd	seedling, flowering, fruit enlargement	0.2 - 0.4	50
Ladyfinger	seedling, fruit enlargement	0.5 - 1.0	60
Muskmelon	early stage of vine growth	1.0 - 1.5	50
Watermelon	crop establishment,vine development, flowring, fruit development	1.0 - 1.5	50

Source: OFWM Field Manual, Volume VI, Irrigation Agronomy, Federal Water Management Cell

Calculating RAW

A step-wise procedure for calculating RAW is given below as guidelines for OFWM staff. Moreover, the values of RAW at different water tensions for different soil textures are also given in Table-6 as a guideline.

Step-1: Identification of effective root zone
Step-2: Determination of soil texture
Step-3: Selection of MAD
Step-4: Calculating/adding up RAW of each soil layer

Rule to Remember

1 mm depth of water = 1 L applied to 1 m^2

EXAMPLE

RAW for Maize in Sandy Loam Soil

RAW = TAW X MAD
TAW = WHC X Rzd
WHC = 104 mm/m (Table - 3 Sandy Loam Soil)
Rzd = 1.2 m (Table - 5 Maize)
TAW = 104 x 1.2 = 124.8 mm/m
MAD = 50% (Table - 5)
*RAW = 124.8*0.5 = 62.4 mm/m*

Table-6: Effect of soil texture on RAW (1kPa = 0.01 bar)

Water Tension	-20 kPA (0.2 bar)	-40 kPa (0.4 bar)	-60 kPa (0.6 bar)	-100 kPa (1 bar)
Soil Texture	Water-sensitive crops such as vegetables	Most fruit and tropical crops	Crops such as maize, soybeans and lucerne	Cotton, sorghum and winter crops
	RAW (mm/m)			
Sand	30	35	35	40
Loamy Sand	45	50	55	60
Sandy Loam	45	60	65	70
Loam	50	70	85	90
Sandy Clay Loam	40	60	70	80
Clay Loam	30	55	65	80
Light Clay	25	45	55	70

Source: Farm Note 543, Calculating Readily Available Water, Department of Agriculture and Food, University of Western Australia

Note: In case of drip irrigation system that does not wet the entire cropped area, RAW (mm/m) is converted into RAW (Liters) as described under preceding Section.

CONVERTING RAW TO LITERS FOR DRIP IRRIGATION

Drip irrigation, the only method, maintains soil moisture contents close to the field capacity (optimum growth) as compared to other conventional/traditional surface irrigation methods. A comparative pattern of moisture availability to crops under different irrigation methods is graphically presented in Figure-7.

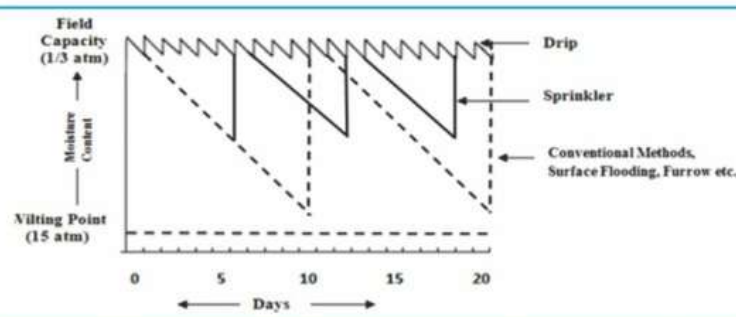


Figure 7: Soil moisture availability to plants under different irrigation methods

Drip irrigation distributes water over a small field area and roots follow this pattern. It is often easier to use liters to describe both water use and storage in the plant root zone, which also allows simple calculation of irrigation time as the discharge from drip systems is commonly reported in liters per hour (LPH). The volume of root zone wetted by the drip system depends on the size and shape of the wetting pattern.

Overlapping Drippers

In overlapping drippers, drip irrigation produces strip or sausage-shaped wetted pattern. The volume of water, in this case, held in the soil can be estimated from the width and length of the wetted strip and the *readily available water (RAW)* in root zone.

Volume of water stored (L) = wetted width (m) x wetted length (m) x RAW (mm)

Example

For example, for a width of 1.5 m wetted, 3 m tree spacing, and root zone RAW of 14 mm, the volume of Readily Available Water = 1.5 x 3 x 14 = 63 liters of RAW per tree.

Non-overlapping Drippers

Where wetting patterns do not overlap, the wetted volume is calculated by assuming a cylinder, sphere or cone-shaped wetting pattern. If there is more than one dripper per plant, multiply this figure by the number of drippers, to get the total litres available for each plant.

Example

For example, if a root zone with RAW of 14 mm is wet by a dripper with a cylindrical wetting pattern of 0.2 m radius, the volume of readily available water = πr^2 x RAW (mm)= 3.14 x $(0.2)^2$ x 14 = 1.8Liter/dripper.

(πr^2 is the area of a circle where pi (π) equals 3.14)

IRRIGATION SCHEDULING METHODS

It is not easy for farmers to adopt proper irrigation scheduling practices because of difficulties in soil moisture measurement. It is, therefore, inevitable to develop and indigenize the irrigation scheduling techniques/methods and tools suited to local conditions, which are simple and easily adoptable by the irrigators. Several methods are available for estimating crop water use ranging from the feel of soil, personal calendar scheduling, soil moisture measurements, evapotranspiration records, plant moisture sensing devices etc. It is important to note that these are all indirect measurements and require some assumptions. In some cases, however, more than one method are used to schedule irrigation. The methods for scheduling irrigation can broadly be classified in three categories.

- **Observational**
- **Soil Moisture Measurements**
- **Evapotranspiration Calculations**

These methods vary in complexity and may require the use of technology. Each method has strengths and weaknesses and it is often recommended that more than one method is used. A common and widely used irrigation criterion is soil moisture status. Table-8 depicts an overview of different methods of irrigation scheduling, its advantages and disadvantages.

Feel and Appearance

This method is based on appearance of the plant and soil in response to water stress. This is the oldest and most commonly employed way for guessing soil moisture content for irrigation purposes. It is based on personal experience of the irrigator by observing the crop condition e.g. change in color of the plant canopy, curling of the leaves, plant wilting condition etc. These changes can only be detected by looking at the crop as a whole, rather than individual plants. The stressed crop appearance changes from vigorous to slow or even no growth as the young light green leaves become darker, grayish, and dull in color.

This method is quick, easy, and popular because it does not require any equipment or technical support. It may, however, not always be much accurate as extensive experience is required to use it effectively. In addition, the moisture stress may have already caused significant damages for most crops by the time the symptoms are evident, leading to huge yield losses. The irrigator should not wait for the appearance of wilting symptoms, especially in the critical stages of crop growth. It is recommended that visual observation in combination with other methods may be used for effective irrigation scheduling.

Soil Moisture Measurements

The measurement of soil moisture content through instruments placed at various depths in the root zone allows monitoring the water available to plants. The sensors buried in the soil or placed on the soil surface, measure properties like conductance of electric current (conductivity meters), resistance to current flow (resistivity meters) and time elapsed in conductance (time domain reflectometry) that are related to soil water content. There is a wide range of soil moisture monitoring equipment/techniques currently available for estimating soil moisture. The same includes tensiometers, gypsum blocks, neutron probes, capacitance devices, soil moisture sensors, time domain reflectometry, time delay transmission, FullStop (wetting front detector) etc. See *'Modern Irrigation Technologies and Practices'* technical brochure published by OFWM, Punjab, Lahore.

Evapotranspiration based Crop Water Budgeting

There are methods that account for the amount of water lost by crop evapotranspiration (ET) and the amount, which enters the soil reservoir as effective rain/irrigation. The logic behind the water budget technique is to apply water equivalent to the accumulated ET losses since the last irrigation. The soil profile is thus recharged to full capacity and the crop starts to evapotranspire water as the cycle begins again. If full recharge is not desired or not possible, the new balance can be determined from the net irrigation amount or by field observations. This approach attempts to represent the physical process of water movement into the soil, within the soil, and through the plant. As such, extensive data and experience are required to obtain an accurate crop water budget. The limitation of this type of irrigation scheduling is its complexity.

Table 8: Comparison of commonly used methods for irrigation scheduling

Method	Irrigation criterion	Measured parameter	Equipment needed	Advantages	Disadvantages
Feel and Appearance	soil moisture content	soil moisture content by feel and appearance	hand probe	• easy to use • simple • Improve accuracy with experience	• less accurate • field work involved in taking samples
Gravimetric Method	soil moisture content	soil moisture content by taking samples	auger, caps, oven	• high accuracy	• labor intensive including field work • time g ap between sampling and results
Tensiometers	soil moisture tension	soil moisture tension	tensiometers including vacuum gauge	• good accuracy • quick	• needs maintenance • breaks at tensions above 0.7 atm
Electrical Resistance Blocks	soil moisture tension	electric resistance of soil moisture	resistance blocks AC bridge (meter)	• instantaneous reading • works over larger range of tensions • can be used for remote reading	• complex • affected by soil salinity • less accurate at low tensions • needs some maintenance and field reading
Water Budget Approach	moisture content	climatic parameters: temperature, radiation, wind, humidity and expected rainfall, depending on model used to predict ET	weather station or available weather information	• no field work required • flexible • forecast irrigation needs • schedule many fields	• needs calibration and periodic adjustments • cumbersome without computer
Atmometer	moisture content	reference ET	atmometer gauge	• easy to use • direct reading of reference ET	• needs calibration

WATER MANAGEMENT ACTIVITIES

LASER Land Leveling

Watercourse Improvement

Sprinkler Irrigation

Drip Irrigation

Bed & Furrow Technology

Solar Water Pump

Hydro Flume Irrigation

Flexible Pipe Irrigation

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