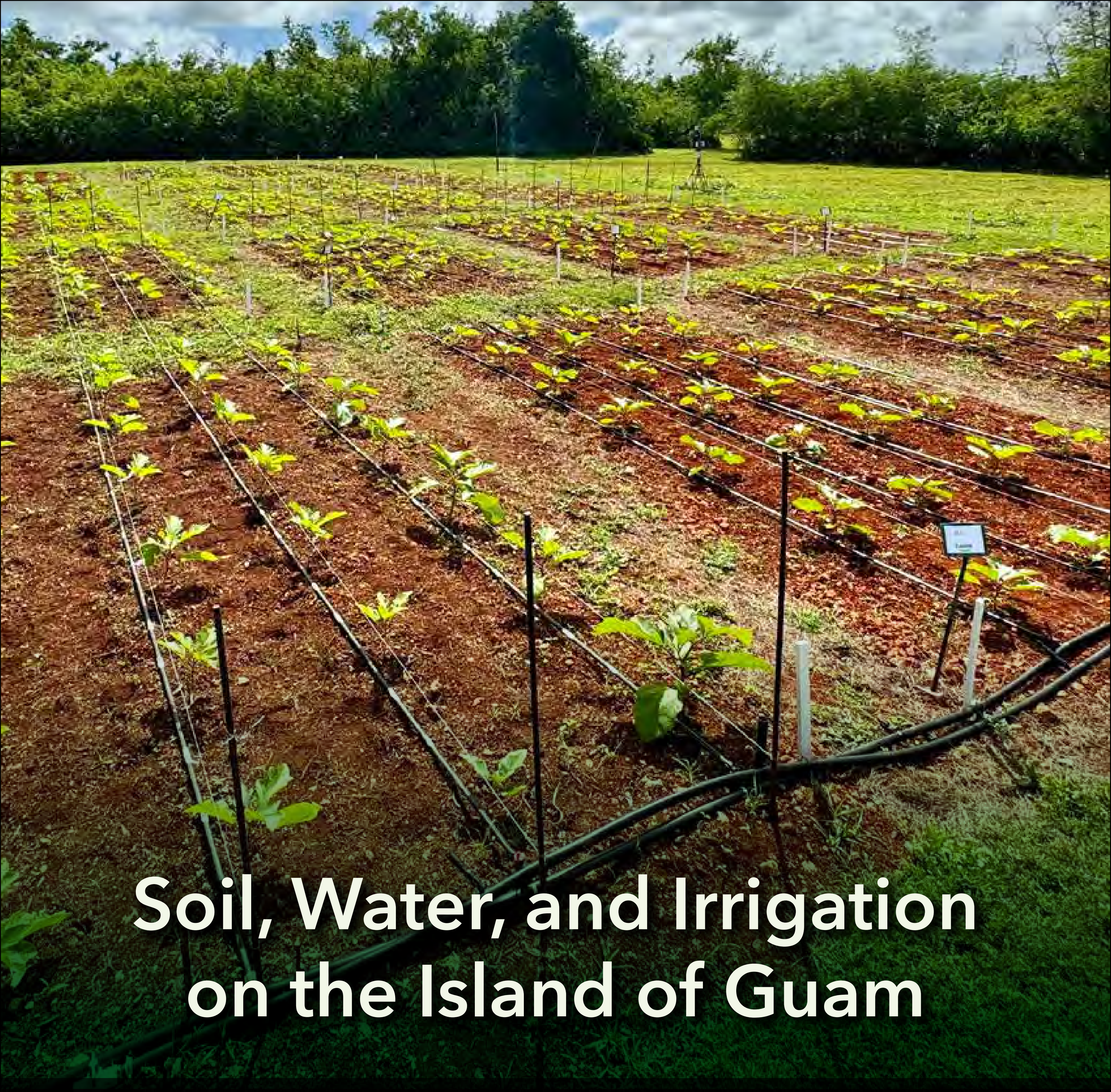

Soil, Water, and Irrigation on the Island of Guam

Mohammad H. Golabi, Ph.D.
Robert F. Bevacqua, Ph.D.
Ferdinand P. Galsim, M.S.
Clancy Iyekar, M.S.

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WESTERN PACIFIC TROPICAL
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WRITTEN BY	Mohammad H. Golabi, Ph.D. Robert F. Bevacqua, Ph.D. Ferdinand P. Galsim, M.S Clancy Iyekar, M.S.
REVIEWED BY	Adrian Ares, Ph.D.
EDITED BY	Jackie Hanson
LAYOUT BY	Conrad Calma

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PART I:
WATER RESOURCES AND SOIL MOISTURE REGIMES IN THE SMALL TROPICAL ISLANDS OF MICRONESIA

Section 1: Background

The Pacific, Indian, and Atlantic oceans and smaller seas, such as the Caribbean, are home to various small tropical islands. These islands rely on effective soil water management to maintain their agricultural production and preserve their precious water resources. Small islands often have very limited water resources. Some lack surface water and rely on thin, underground freshwater-lens aquifers (Falkland T., 1999). Due to their location, surrounded by vast bodies of water, these islands are especially susceptible to natural disasters, such as floods, tropical cyclones, earthquakes, volcanic eruptions, and tsunamis. The potential impact of rising sea levels adds to their challenges (Shultz, JM et al., 2016).

The agriculture sector is the largest consumer of fresh water worldwide, accounting for an average of 70% of all water withdrawals. Irrigated agriculture occupies less than 20% of cultivated land, yet it produces 40% of the world's food supply (The World Bank, 2022) and nearly 60% of cereal production in developing nations (FAO, 2003b).

In certain islands, agricultural and natural plant ecosystems rely heavily on rainfall, which may occur seasonally. The population's ability to optimize water use efficiency for agricultural activities in these islands will be contingent upon their financial capacity and scientific progress. Due to the scarcity of water resources in small islands, agricultural activities need to utilize all available advanced water management techniques. Therefore, understanding soil water management is crucial for optimal water utilization when producing crops under irrigated systems (Golabi, Mohammad H., n.d.).

Section 2: Climatic and Hydrological Characteristics of Small Tropical Islands

2.1. Climate

The climate in tropical small islands is variable based on time and location. Warm and moist northeast and southeast trade winds typically affect the tropical regions in the Pacific and Indian Oceans. The important characteristics of rainfall from a water resources viewpoint and soil water storage for an island are its spatial and temporal distribution.
Small islands in tropical regions mostly experience rainfall as their primary form of precipitation. However, dew condensation, snow, and fog interception may also occur in highland areas. Rain patterns on these islands can either be a continuous, long rainy season with no significant dry spell or two rainy seasons with a short dry period in between, accompanied by a more pronounced dry season during the low sun period. It's important to note that while these are general patterns, local variations may occur (Golabi, Mohammad H., n.d.).

The climate of an island plays a major role in its hydrological cycle and affects the availability and changes in water resources. Precipitation and evapotranspiration are critical hydrological parameters (Golabi, Mohammad H., n.d.). Rainstorms are usually brief, but powerful, with larger drops that put significant energy onto soil particles. The rainfall intensity in these areas can be two to four times greater than in temperate regions.

2.2. Hydrologic Characteristics

The humid tropics are areas where rainfall is greater than the amount of water that could potentially evaporate and transpire potential evapotranspiration (PET) for a minimum of nine months annually. During drought, PET exceeds the amount of water evaporated and transpired (actual evapotranspiration, or AET). As a result, soil water storage capacity is crucial for plant growth during dry periods. Therefore, increasing water infiltration storing it in the root zone, and decreasing its losses by evaporation, deep seepage, and use by weeds is critical for minimizing the risk of agronomic drought and its adverse effects on agronomic productivity (Golabi, Mohammad H., n.d.).

Section 3: Water Resources

3.1. Surface Water

In areas where the conditions are favorable, small islands with high elevations, also known as high islands, can have surface water in the form of temporary and permanent streams, springs, fresh-water lagoons, lakes, and swamps. The occurrence of permanent streams and springs is mainly observed in high volcanic islands, where the rock's permeability is low. On the other hand, low-lying islands usually do not have surface water.

3.2. Groundwater

On small islands, groundwater can take the form of either perched aquifers, which are close to the soil surface, or basal aquifers, which are at a lower level. Perched aquifers are typically found above horizontal confining layers known as aquicludes. Basal aquifers can be unconfined, partially confined, or confined freshwater bodies that form at or below sea level. However, basal aquifers, such as on volcanic and bedrock islands, are not very common on certain islands with low permeability. Because of the interaction between freshwater and seawater, basal aquifers are vulnerable to saline intrusion. They must be managed carefully to prevent over-exploitation and seawater intrusion, as in places like Saipan . The importance of surface water versus groundwater on these islands varies depending on the island's characteristics. However, groundwater tends to be the more valuable resource of the two. Therefore, it is important to carefully manage groundwater use for agriculture during dry seasons to preserve this scarce resource.

3.3. Hydrogeology

The distribution of groundwater on an island is greatly affected by hydrogeological factors, including the soil's permeability and porosity and the existence and spread of karstic features, such as small cave systems and solution cavities in rocks and sediments.

3.4: Freshwater Lens

The term "freshwater lens" can be misleading, implying a distinct freshwater aquifer. There is no clear boundary between fresh water and seawater, but rather a transition zone.

3.5. Factors Affecting Freshwater Resources

(a) Physiography
(b) Climate and hydrology
(c) Geology and hydrogeology
(d) Soils and vegetation
(e) Human impacts, including over-utilization and pollution from a variety of sources.

3.6. Other Water Sources

Small islands have several sources of fresh water, including rainwater collected from natural or artificial surfaces, desalinated seawater, brackish groundwater, and treated wastewater. Except for rainwater collection, these water sources are often called "non-conventional" water. The conventional water sources on these islands are rainwater, surface water, and groundwater (Golabi, Mohammad H., n.d.).

Section 4: Physiography

Based on their topography, islands are commonly categorized as "high" or "low." This classification differentiates islands with surface water resources, such as streams and rivers, from those without significant surface runoff.

High islands are usually volcanic, while low islands are typically coral atolls. However, raised coral limestone islands are an exception as they are topographically high but generally lack surface water resources.

Surface water resources can be found in temporary and fast-moving streams in regions with high volcanic islands. Islands with low permeability soil may have small but long-lasting streams unless there is a prolonged period of drought. After rainfall, surface runoff occurs quickly and decreases within a few hours.

Regarding low islands, the height above sea level and the width of the fringing reef and sea level movements caused by tides, pressure changes, and longer term influences determine the island's risk of being overwhelmed by storm surges. This may cause saltwater to mix with the island's surface water (Golabi, Mohammad H., n.d.).

Section 5: Evapotranspiration

Evapotranspiration (ET) plays a crucial role in the hydrological cycle of small tropical islands. ET is the process of water loss to the atmosphere through evaporation from water bodies, soil, and plant transpiration (Abeysiriwardana, H.D. et al., 2022). It can result in the loss of more than 50% of rainfall annually. It can even exceed the amount of rainfall during dry periods or droughts, whether for individual months or consecutive months.

Section 6: Soils

In the humid tropics, most soils are unstable in structure and easily crumble when exposed to rain. This occurs because intense storms cause the soil to dry rapidly, forming a crust on the surface. This crust lowers the rate at which water can seep into the soil, causing a decrease in soil moisture and an increase in water runoff. This effect is seen even during light rainfall and becomes more pronounced during heavy rainfall.

Soils with no protective vegetative cover are more prone to poor structure, which can lead to reduced infiltration. This is often caused by low levels of organic matter in the soil, and deforestation and cultivation can exacerbate the issue and make tropical soils more susceptible to erosion.

The amount of water soil can hold is directly related to how deep the soil is and how thick the porous rocks or geological sediment are. Most islands have a thin layer of soil unless there has been a special event like volcanic ash deposition. Thicker soils can hold more water than thinner soils.

The soil's ability to retain water is essential in determining evapotranspiration and recharge. Soils with fine grains and high retention capacity are more likely to favor the evapotranspiration of rainwater, which reduces recharge. However, soils with coarse grains and low water retention capacity allow rainwater to infiltrate quickly below the root zone, which reduces evaporative losses and increases recharge.

In times of extended drought, clay soils may develop cracks that allow for swift water infiltration if the cracks are open. However, after a rainstorm, the clay swells and closes the cracks, which reduces recharge. As a result, the best water management strategy is to store and conserve water in the soil's root zone. This approach enhances efficient water usage, boosts productivity, and sustains agricultural sustainability. Due to this, evaluating soil moisture levels and taking accurate measurements become crucial factors in crop production and agricultural sustainability (Golabi, Mohammad H., n.d.).

Section 7: Water Balance of Small Islands

7.1. General Principles

Studying the hydrological cycle on small islands is a unique experience since one can observe everything in a small area. Scientists use a water balance equation to analyze the various components of the cycle. The equation looks at inputs, outputs, storage, and measurement errors or unknown factors.

7.2. Water Balance at the Surface

The water balance equation (or recharge model) for the surface of a small island can be expressed generally as:

$$R = P - [ETa + SR] \pm dV$$

Where:

P = precipitation (most commonly rainfall)
ETa = actual evapotranspiration (including interception)
SR = surface runoff
R = recharge to groundwater
dV = changes in soil moisture content

In low-lying islands with porous soils and subsurface geology, such as coral atolls and small limestone islands, surface runoff is minimal or nonexistent. As a result, the water balance equation simplifies to:

$$R = P - ETa \pm dV$$

The water balance procedure is more complicated for raised atolls and limestone islands due to typical water table depths of 10-100 meters and frequent karstic formations (Golabi, Mohammad H., n.d.).

Land Use: Land management is important for protecting freshwater lenses from contamination. This is particularly important on islands with highly permeable soils (i.e., northern Guam) and shallow water tables, making groundwater very susceptible to pollution.

Water reserves or protection zones should be established wherever possible. Such reserves should disallow land uses that have the potential for polluting water resources, including agricultural, residential (septic tanks), commercial, and industrial development. Land use, soil management, and cropping systems are crucial for sustainable water and soil management.

CASE REVIEW:
GUAM'S WATER REGIMES

Section 8: Hydrogeologic Characteristics of the Island of Guam

The surface of northern Guam, a relatively small island in the western Pacific, is a gently sloping limestone plateau occupying about half of the island's area of 550 km2. The southern portion of the plateau rises from sea level to 60 meters, while the northern portion has a maximum elevation of about 180 meters.

The average annual rainfall in Guam is about 2.54 meters (100 inches), about 70-80% of which falls during the wet season from July to December. On the other hand, monthly water table fluctuation across the lens of northern Guam appears to be relatively uniform (Golabi, Mohammad H., n.d.).

Hydrological measurements of the water levels in observation wells have shown that stormwater from heavy rainfall can reach the water table in hours. This is true despite the vadose zone's large thickness (60-180 meters). However, field observation on the island of Guam has revealed that flow through the vadose zone is quite complex (Golabi, Mohammad H., n.d.).

Section 9: Climate and Rainfall in Guam

The climate in Guam is tropical, with a wet-dry season. The average yearly temperature is 28°C (82°F) with a relative humidity ranging from 60-

100%. The dry season occurs from January to May, while the wet season occurs from July to November. June and December are transitional months (Golabi, Mohammad H., n.d.).

In a 14-year period, the average annual rainfall in Guam was approximately 2.4 meters (94 inches). Rainfall in Guam is seasonal and periodic. Therefore, measuring aquifer recharge requires accurately estimating water loss from rainfall. Evapotranspiration is the leading cause of soil water loss.

Section 10: Soils of Guam

Seventeen different soil series have been mapped in Guam. They are grouped into three primary categories:

1. Soils over limestone
2. Soils on volcanic uplands
3. Soils on bottomlands and coastal margins

Most of Guam's limestone-derived soils are in the north, while volcanic soils are mainly found in the south. The shallow "Guam Soil Series" covers roughly 24% of the island's land area of 55,445 hectares, or 214 square miles (Golabi, Mohammad H., n.d.).

The southern lands of Guam are known as badlands due to severe erosion caused by overland flow, wind, and rain. This erosion occurs rapidly because the sloping sites are devoid of vegetation. Badlands are a significant source of sediment in the local watershed, and their numbers and sizes are increasing due to activities such as off-roading and wildfires.

This accelerated erosion poses a threat to both the soil resource base and the downstream environment. This threat is especially severe in tropical landscapes, particularly small island settings like Guam (Golabi, Mohammad H., n.d.).

Agricultural soils in Guam face a major issue of low organic matter content in eroded areas, often due to vegetation clearing and burning. Therefore, soil water characteristics and measurements become essential parameters for management purposes, ensuring soil productivity for agricultural sustainability in Guam. Moreover, soil and water conservation practices are necessary and crucial for agricultural sustainability in Guam and neighboring islands in the western Pacific.

Section 11: Soil Water

Water is an essential element for all living organisms. It plays a crucial role in chemical reactions that release or absorb nutrients, regulate acidity levels, and break down minerals to contribute to the salinity of the ocean. It has a simple molecular structure (Figure 1), consisting of one oxygen atom and two smaller hydrogen atoms. Each hydrogen atom shares its single electron with the oxygen atom (Golabi, Mohammad H., n.d.).

Due to their asymmetry, water molecules have an electropositive side with hydrogen atoms and an electronegative side with an oxygen atom.

Water's polarity is crucial in various reactions in soil and environmental sciences. This characteristic describes how water molecules interact with each other. When one molecule's positive hydrogen end attracts another molecule's negative oxygen end, they form a chain-like

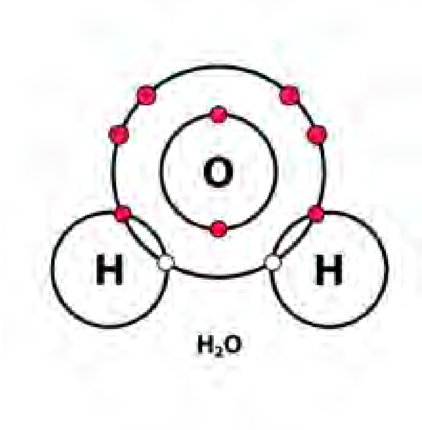

Figure 1. Structure of water molecule

grouping referred to as a polymer, as shown in Figure 2. This property explains why molecules are drawn to electrostatically charged ions and colloidal (microscopic soil particles) surfaces. Cations like Na+, K+, and Ca+ get hydrated as they are attracted to the negative end of oxygen in water molecules. The hydrogen atoms' ability to act as links between water molecules is called hydrogen bonding (Figure 2).

Hydrogen bonding is responsible for two forces that affect the retention and movement of water in soils. Cohesion refers to the attraction between water molecules to each other, while adhesion refers to the attraction between water molecules and solid surfaces (adsorption).

Due to adhesion (adsorption), certain water molecules cling tightly to the solid surfaces of soil. These tightly bonded water molecules then hold onto other water molecules, which are further from the solid surfaces, through cohesion. The combined forces of adhesion and cohesion enable soil solids to retain water, regulate its movement, and manage its use (Golabi, Mohammad H., n.d.).

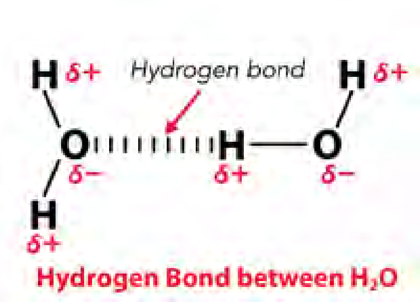

Figure 2. Molecules whose positive and negative charge centers do not coincide are termed polar molecules. This figure also shows cohesion and adhesion in the water molecule chain.

Section 12: Water Movement in the Soil

Capillary Fundamentals and Soil Water:
Capillarity refers to water movement up a wick when the lower end is submerged. Two forces cause this phenomenon:

1) The attraction of water for the solid walls of channels through which it moves (*adhesion* or *adsorption*).
2) The surface tension of water is due largely to the attraction of water molecules to each other (*cohesion*) (Figure 2).

Section 13: Soil Moisture Content (θ) and Soil Water Potential (Ψ)

The retention and movement of water in soils, its uptake and translocation in plants, and its loss to the atmosphere are all energy-related phenomena.

13.1. Sources Affecting Potential Energy

Three important forces affect the energy (soil water potential) level of soil water:

1. **Matric potential** – The capillary, adhesion, or attraction of the soil matrix (solid) for water, provided by the adsorption of water molecules for each other.
2. **Osmotic potential** – The attraction between ions and other solutes and water can lower the energy level of water in the soil. This results in the osmotic movement of pure water into a solution across a semi-permeable membrane, indicating the lower energy state of the solution. This force can lead to wilting in soils with high salt content.
3. **Gravimetric potential** – The gravimetric potential pulls water downwards, and the soil water potential comprises several forces. Each force accounts for a portion of the total soil water potential, called gravitational, matric, and osmotic pressures. These forces create differences in energy levels as described in the equation below:

- Gravitational potential

(Ψ_g)
- Matric potential (Ψ_m)
- And Osmotic (Ψ_o)

Therefore, the total water potential is:

$$(\Psi_t) = (+\Psi_g) + (-\Psi_m) + (-\Psi_o)$$

13.2. Measuring Soil Water Content and Water Potential

Two general types of measurements are applied to soil water (Golabi, n.d.):

1. Water content(Ψ) may be measured by:
   a) Directly by weighing the soil sample before and after drying:
   % Soil moisture = [(wet weight – dry weight) / (dry weight)] x 100
   b) Indirectly by using the following instrumentations used by soil scientists and technicians for measuring the water content of the soil:
      - Gypsum block (electrical resistant block) – uses two electrodes for measuring water content
      - Neutron probe – using radiation to measure water content
      - Time Domain Reflectometry (TDR) - non-destructive method used to determine soil water content.
2. Water potential (Ψ) may be measured by:

   Tensiometer – measures the tendency with which water is held in soils and expressed as soil water potential (refer to section 13.1).

$$(\Psi_t) = (+\Psi_g) + (-\Psi_m) + (-\Psi_o)$$

13.3. Soil Water Movement

There are multiple types of water movement in the soil, which are as follows:

1. Saturated water flow
   - When all soil pores are saturated, water flow is then controlled by gravity.

2. Unsaturated flow
   - Controlled by differences of matric potential between moist areas and nearby drier areas.
3. Vapor movement
   - Internal vapor movement within the soil pore spaces.
   - Controlled by vapor pressure and temperature differences within the soil profile.
   - External vapor movement occurs at the soil surface, where water vapor is lost by surface evaporation.
4. Infiltration: Entry of water into the soil matrix
   - The infiltration rate determines the amount of runoff during rainstorms and the potential hazards of erosion. Once infiltration stops due to soil crust, runoff begins.
   - Infiltration also determines the water economy of the soil. Higher infiltration will increase water storage in the soil matrix.

Section 14: Soil-Plant Water Relations

Water is crucial in many cellular activities and physiological processes within plants. Without water, a cell cannot enlarge and stretch its wall, which is essential for plant growth. As a result, visual water stress symptoms, such as wilting leaves, can occur. However, excessive soil water can also have negative effects on plant growth. As water levels rise, they displace more oxygen from soil pore space, which inhibits respiration. The plant then displays water stress symptoms, such as reduced vigor, chlorosis, and in severe cases, death.

Section 15: How Much Water is Held in the Soil?

Water management is

significantly influenced by the ability of soil to hold water. This is because crops rely on soil for water and plant nutrients. The capacity of soil to retain water plays a crucial role in satisfying plant needs between irrigation or rainfall periods. The soil's water-holding capacity determines the rainfall or irrigation water retained. Silt loams have a higher capacity to hold water and can provide water to plants longer than fine sands, with a low water-holding capacity. A soil's texture, which depends on the mixture of various sizes of soil particles, is closely linked to its water-holding capacity (Golabi, Mohammad H., n.d.).

Section 16: Soil-Water Conditions and Categories

There are three categories of soil water: 1) excess soil water or gravitational water, 2) available soil water, and 3) unavailable soil water. Excess soil water, also known as gravitational water, drains easily due to gravity. This water is only present in the soil from when it's saturated until it reaches "field capacity." Available soil water is held in the soil by capillary forces and can be used by plants. This type of soil water is crucial for crop production and is held between "field capacity" and the "wilting point." Plants can use up to 50% of available water without experiencing stress. However, stress can occur if less than 50% of the available water remains. Plants cannot extract water held too tightly to soil particles by adsorptive forces. This water remains in the soil (unavailable) when it is drier than the wilting point (Golabi, Mohammad H., n.d.).

Section 17: What is Soil-Water Availability to Crops?

17.1. Ranges of Available Water to Plant

The range of water available to plants is between field capacity (FC) and the permanent wilting point (PWP).

17.2. Field Capacity

Refers to the maximum amount of water a soil can hold at the upper limit of its available water capacity. This measurement is determined by calculating the amount of water left in the soil after it has been saturated and drained for 24-48 hours. As the soil continues to dry, gravitational drainage slows down significantly. The soil is at field capacity when all the gravitational water has been drained, and a vertical movement of water due to gravity is negligible.

The permanent wilting point is when a plant no longer has access to water. This marks the lower limit of the available water range. Once a plant has depleted all available water, it will wilt and may not be able to recover.

17.3. Available Water Capacity

Refers to the maximum water a soil can hold between field capacity and wilting point. This capacity varies depending on the soil texture.

Section 18: Soil Parts (Phases): Air, Water, Solid Relations

Soil comprises three major parts or phases: air, water, and solids (Figure 4).

The soil framework comprises the solid component, a mix of

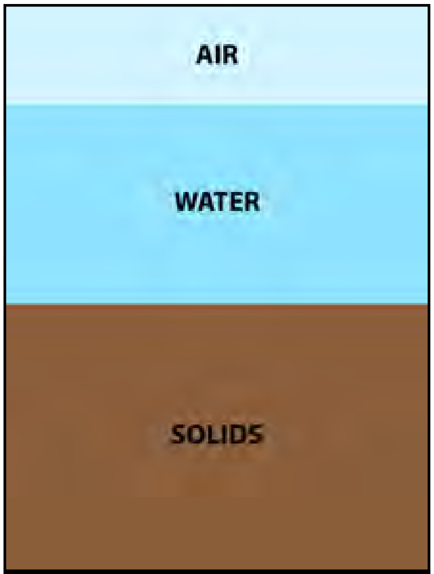

Figure 3. Schematic representation of soil as a dynamic system composed of air, water, and solids. (Evans, R., *et al.*, (n.d.).

minerals and organic matter. The mineral fraction includes sand, silt, and clay particles.

The proportion of the soil occupied by *water* and *air* is called the *pore volume*. The pore volume is generally constant for a given soil layer but may be altered by tillage and compaction. The ratio of *air* to *water* stored in the pores changes as water is added to or lost from the soil.

Water is lost through surface runoff, evaporation (direct loss from the soil surface to the atmosphere), transpiration (losses from plant tissue), and either percolation (seepage into lower layers) or drainage. Water is added by rainfall or irrigation, as shown in Figure 5.

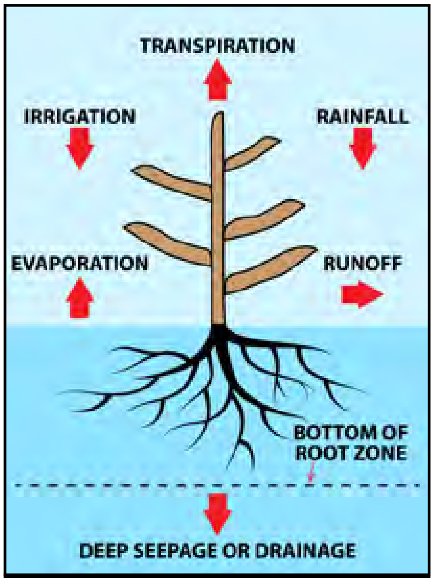

Figure 4. Source and fate of water added to a soil system. (Evans, R., *et al.*, (n.d.).

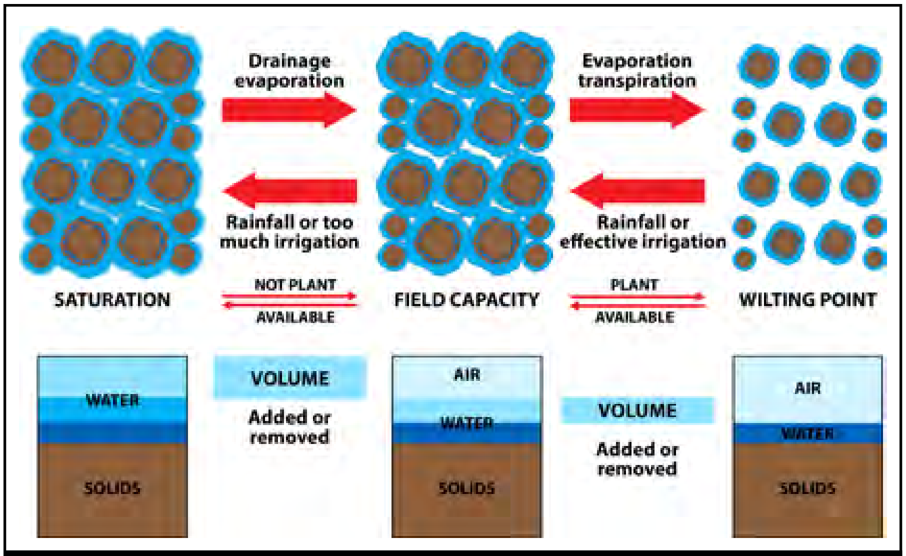

Figure 5. Relationship between plant-available water and water distribution in the soil. (Evans, R., *et al.*, (n.d.).

After the process of redistribution, the soil reaches field capacity, which is the condition where it holds the maximum amount of water that plants can use.

Plant-available water (PAW) refers to the amount of water stored in soil that is accessible to plants.

Section 19: Soil-Water and Plant Stress

The amount of plant-available water (PAW) varies based on the soil type and crop. Figure 6 illustrates the relationship between plant-available water and water distribution in the soil. Even if there is enough PAW, plants may still wilt during periods of high evapotranspiration (ET).
The term "evapotranspiration" describes how water is lost from the soil's surface to the atmosphere through evaporation and also through the transpiration of plants. This process is affected by atmospheric conditions and

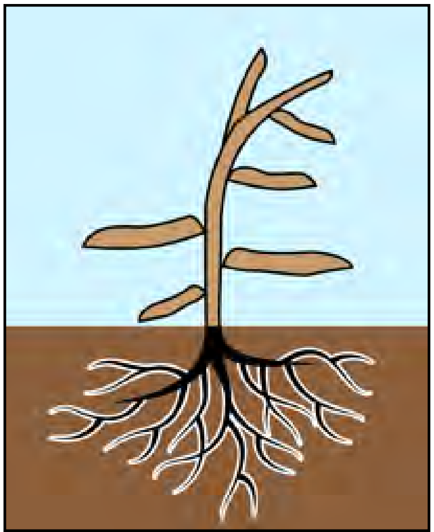

Figure 6. As the plant extracts water, the soil immediately adjacent to the roots (light areas) dries (Evans, R., *et al.*, (n.d.). Note: If the rate of water movement from moist zones is less than the ET, the plant temporarily wilts.

is typically highest during the day. If the process is too high, it can cause plants to wilt during the daytime because they are using up more water than can be replaced. For plants to survive, they must absorb water from the soil around their roots. As the soil begins to dry up, water must move through it to reach the roots. (Figure 7).

During the night, when ET levels decrease to almost zero, water gradually flows from the wetter soil to the drier area around the roots. This allows the plant to regain its turgor and stop wilting, as shown in Figure 8. This cycle of wilting during the day and recovering at night is known as temporary wilting. By scheduling irrigation properly, the duration of temporary wilting can be minimized, resulting in healthier crops.

If less than half of the plant-available water (PAW) has been used up, most crops can recover from temporary wilting overnight. As a result, it is generally recommended that the allowable depletion be set at 50 percent (as shown in Figure 9). However, the recommended depletion level also depends on the soil type. Sandy soils may require a depletion volume of 40 percent or less, while clayey soils may require a greater than 60 percent depletion volume. Additionally, the allowable depletion level depends on the crop type, developmental stage, and susceptibility to drought stress. For instance, drought-sensitive crops like vegetables may only have an allowable depletion level of 20 percent during critical developmental stages. On the other hand, drought-tolerant crops like soybeans or cotton may have an allowable depletion level of up to 70 percent during non-critical periods.

Section 20: Crop-Water Supply and Irrigation Scheduling

20.1. Plant Factors

Three plant factors must be considered in developing a sound irrigation schedule (Golabi, Mohammad H., n.d.):

1. The crop's effective root depth
2. Crop's moisture-use rate
3. Crop's sensitivity to drought stress (the amount that crop yield or quality is reduced by drought stress).

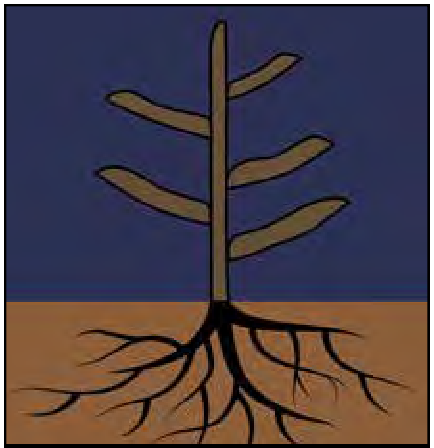

Figure 7. At night, water moves to eliminate dry zones around roots and the plant recovers from wilting (Evans, R., *et al.*, (n.d.).

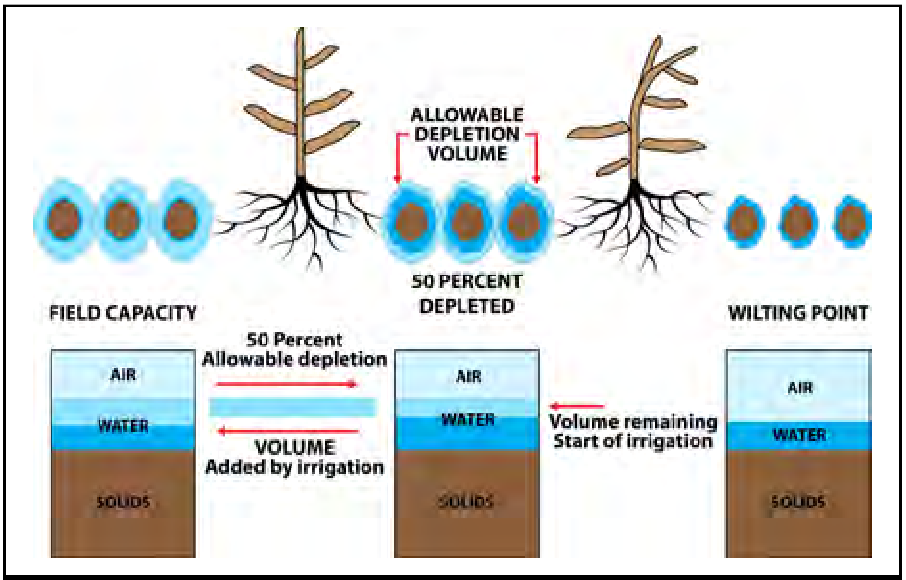

Figure 8. Showing the relationship between water distribution in the soil and the concept of irrigation scheduling when 50 percent of the PAW has been depleted (Evans, R., *et al.*, (n.d.).

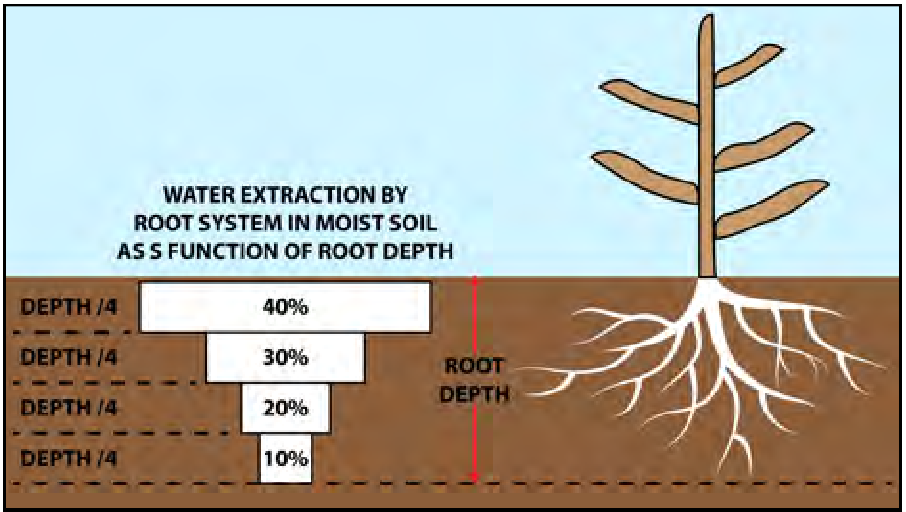

Figure 9. The distribution of the roots in the soil influences the amount of water extracted by plants (Evans, R., *et al.*, (n.d.).

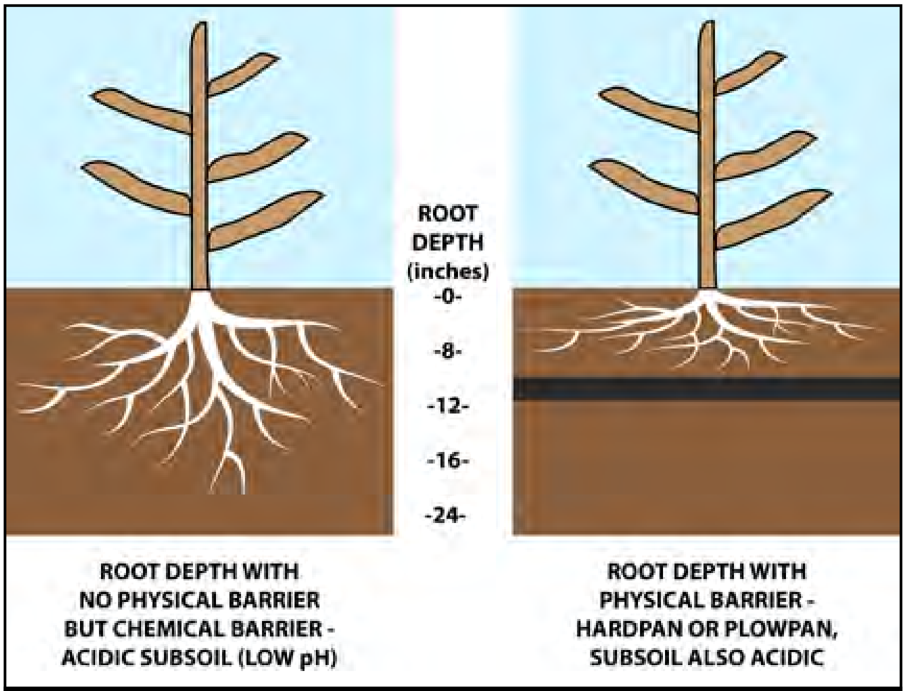

Figure 10. Soil properties that influence the plant's rooting depth (Evans, R., *et al.*, (n.d.).

20.2. Effective Root Depth

Effective root depth is an important concept in agriculture, referring to the depth of soil where crops can extract most of their water. The crop and soil properties determine this depth and vary depending on the plant species. The potential rooting depth is the maximum depth a crop can reach when grown in moist soil with no barriers to root elongation. However, water uptake by a crop is most closely related to its root distribution in the soil. About 70% of a plant's roots are found in the upper half of its maximum rooting depth. While deeper roots can extract moisture to keep the plant alive, they cannot extract enough water for optimum growth. In the presence of adequate moisture, water uptake by the crop is about the same as its root distribution, with 70% of the water used coming from the upper half of the root zone (Figure 10). This zone is known as the effective root depth (Golabi, Mohammad H., n.d.).

20.3. Soil Influence on Effective Root Depth

Soil barriers, such as chemical or physical restrictions, often limit the depth to which crops can effectively root. Soil with a pH of approximately 4.5 to 5.0 can act as a chemical barrier, hindering root growth, as illustrated in Figure 11. Soil pH below 2 feet rarely improves by liming practices. Physical barriers like shallow soils or compacted tillage pans can also limit root penetration below the plow depth, typically less than 12 inches, unless subsoiling is done (Golabi, Mohammad H., n.d.).

20.4. Crop Development

The effective depth of roots is affected by the crop's

Figure 11. Corn rooting depth during various stages of development (Evans, R., *et al.*, (n.d.).

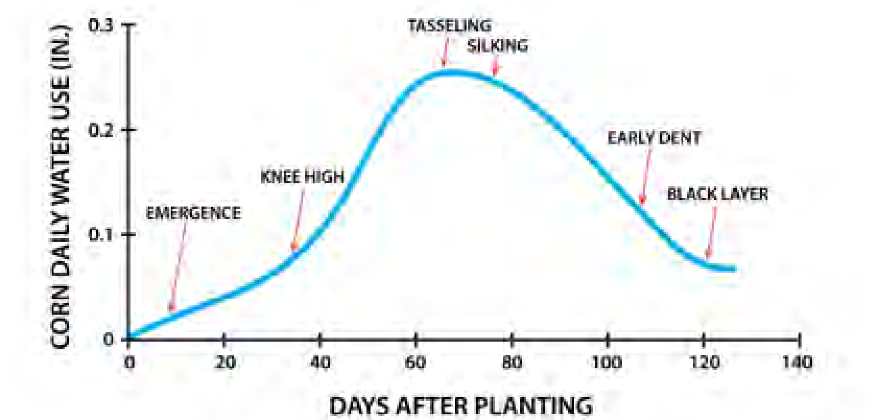

Figure 12. The stage of development influences corn's daily water use (Evans, R., *et al.*, (n.d.).

growth stage. The effective root depth increases as the plant grows until it reaches the reproductive stage. Once this stage is reached, the effective root depth stays the same. Figure 12 shows corn's maximum and effective rooting depths at different stages of development (Golabi, Mohammad H., n.d.).

20.5. Crop Water Use Rate

To schedule irrigation accurately, estimating the rate at which plant-available water (PAW) is extracted is important. The water use rate depends on the crop's development stage, as shown in Figure 13. For instance, during the pollination period (65 to 75 days after planting), corn requires water three times faster (0.25 inch per day) than during the knee-high stage (35 to 40 days after planting, 0.08 inch per day) (Golabi, Mohammad H., n.d.).

20.6. Crop Sensitivity to Drought Stress

When crops are subjected to drought stress, the extent of the damage to their yield or quality depends on the stage of their development. For instance, corn is particularly vulnerable to dry conditions during the silking stage, as illustrated in Figure 14. The silking stage is a crucial point in determining the potential yield of a crop (Bayer Crop Science, 2020). At this stage, a given stress level can result in a yield reduction four times greater than the knee-high stage (Evans, R., et al., (n.d.). Therefore, applying irrigation water during silking is four times more beneficial than applying the same amount at the knee-high stage. This knowledge is particularly valuable when water supply or irrigation capacity is restricted.

The most critical time for irrigation typically begins just before the reproductive stage and lasts for approximately 30 to 40 days until the end of the fruit enlargement or grain development stage (Figure 14). If irrigation is planned before the crop root system is fully developed, the amount of irrigation to be applied should be determined based on the depleted PAW within the effective root depth at the time of irrigation. For instance, when corn is at the knee-high

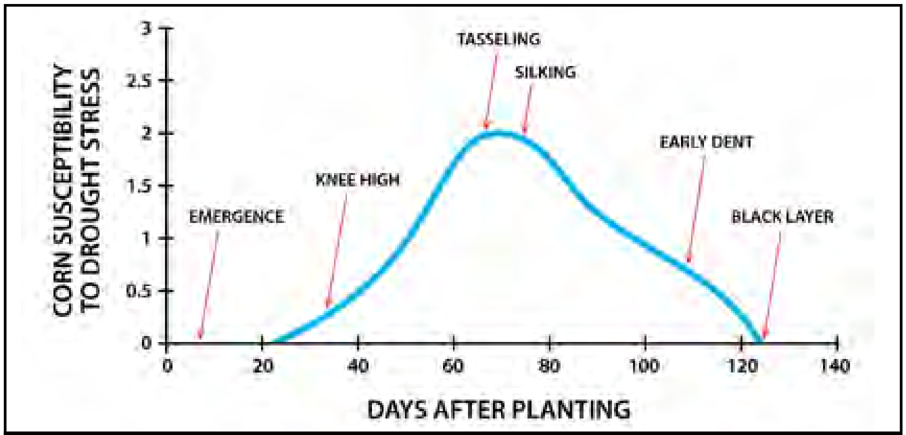

Figure 13. Variation of corn yield reduction caused by drought stress at different stages of development (Evans, R., *et al.*, (n.d.).

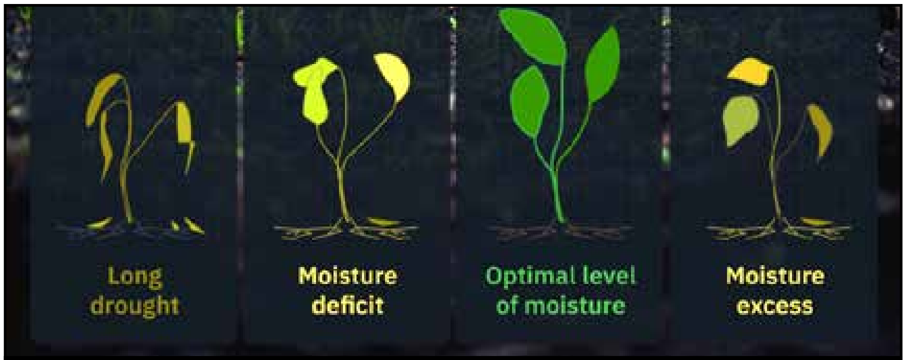

Figure 14. Displays the different levels of soil moisture that directly impact plant growth and yield (Cherlinka, V., 2023).

stage (35 to 40 days after planting), irrigation should only apply approximately two-thirds as much water (Golabi, Mohammad H., n.d.).

Section 21: Impact of Soil Moisture on Plant Growth

The growth of plants is directly affected by the moisture in the soil. This refers to the amount of water in a specific area and the field's overall health (Figure 15). Since plant roots absorb water first, their condition depends on the level of moisture and aeration present. Therefore, soil moisture is crucial in determining the effect on plant growth and yield. The optimal range of soil moisture content for crops varies based on the plant species but typically falls between 20% and 60% (Golabi, Mohammad H., n.d.).

Factors Affecting Soil Moisture

- **Texture:** The finer it is, the more pores and, therefore, better moisture retention.
- **Structure:** A porous and highly aggregated structure can significantly improve the water retention capacity.
- **Organic matter content:** The more organic matter there is, the more significant the water-holding capacity.
- **Density:** The higher the density, the less water penetrates inside.
- **Temperature:** Moisture content is higher at lower temperatures.
- **Salinity:** The higher the salt content, the less water the plants can absorb, as salt is a natural water absorbent.
- **Depth:** This factor affects the amount of water and nutrients plants can access. Deeper soil means there is more availability.

Proper irrigation management is essential in mitigating soil salinity's adverse impact on plant growth and yield. The highest concentration of salt in the soil solution is observed when water content is reduced due to evapotranspiration (Havlin, 2017).

Section 22: Instruments that Measure Water Content or Water Potential

1. **Tensiometer:** A tensiometer measures soil matric potential, known as soil water suction or soil water tension. This tool is

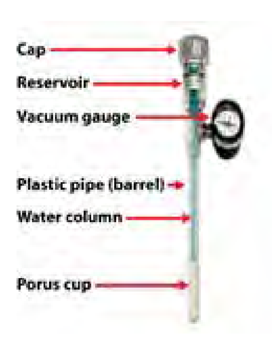

Figure 15
Tensiometer

Figure 16
Gypsum block

Figure 17
Watermark soil moisture sensor and digital meter

Source: www.irrometer.com

commonly utilized in horticultural crops and comprises a cylindrical tube filled with water and sealed tightly. It has a porous cup fixed to its lower end and a vacuum gauge at the top, as shown in Figure 15. The tension measured by tensiometer is equivalent to the force or energy a plant must overcome to extract water from the soil and the force that determines the moisture distribution and transport within the soil.

2. Gypsum block:
   Gypsum blocks (Figure 16) indirectly measure soil moisture by testing electrical resistance between two electrodes in a gypsum block buried in the soil.
3. Watermarks:
   Watermarks (Figure 17) are like gypsum blocks, as they have electrodes embedded in either fiberglass or perforated metal-encased blocks that contain a mixture of sand and gypsum. These sensors have a wide measurement range, from 0 to 239 kilopascals, which makes them ideal for irrigation scheduling in various soil and vegetation applications. They are commonly used due to their versatility and accuracy.

Section 23: Summary

Small-island farmers, such as those in Guam, often face challenges in obtaining fresh water despite being surrounded by vast ocean bodies. In addition, natural disasters such as tropical cyclones, floods, and droughts frequently damage crops and disrupt farming operations. Moreover, the projected rise in sea levels may worsen the situation by causing groundwater to become saline, which would adversely affect farmers' irrigation systems.

To schedule irrigation in an efficient and effective way, it is crucial to comprehend the connection between soil water and plants, as well as understand soil water conditions. This is particularly crucial for crop production and agricultural sustainability, particularly in small islands where fresh water is scarce. Adoption of agricultural technology can also aid in lowering water and fertilizer usage, which in turn can reduce food prices and limit negative environmental impact.

REFERENCES

Abeysiriwardana, H.D., Muttil, N., & Rathnayake, U. (2022). A comparative study of potential evapotranspiration estimation by three methods with FAO Penman–Monteith Method across Sri Lanka. *Hydrology*, 9(11), 206. MDPI AG. Retrieved from http://dx.doi.org/10.3390/hydrology9110206

Bayer Crop Science. (2020). Determining corn growth stages. https://www.cropscience.bayer.us/articles/bayer/corn-growth-stages-and-gdu-requirements

Brady, Nyle C., and Ray R Weil. (2008). The Nature and Properties of Soils. 14th ed. Upper Saddle River, N.J.: Pearson Prentice Hall.

Cherlinka, V. (2023). Soil moisture: Methods of measuring and tools for monitoring. EOS Data Analytics. https://eos.com/blog/soil-moisture

Evans, R., Cassel, D., & Sneed, R. E. (n.d.). Soil, water and crop characteristics important to irrigation scheduling. NC State Extension Publications. https://content.ces.ncsu.edu/soil-water-and-crop-characteristics-important-to-irrigation-scheduling

Falkland, T. (1999). Water resources issues of small island developing states. Natural Resources Forum, 23: 245-260. https://doi.org/10.1111/j.1477-8947.1999.tb00913.x

FAO. (2003b). Issue paper for Ministerial meeting on water for food and agriculture, Kyoto, Japan.

Golabi, Mohammad H. (n.d.). Lecture notes for the Principles of Soil Sciences (AL380). University of Guam. Fall Semester, 2022.

Havlin, J.L., Beaton, J.D., Tisdale, S.L., and Nelson, W.L. (2017). Soil fertility and fertilizers: An introduction to nutrient management. 8th Edition, Pearson India Education Services Pvt. Ltd.

Irrometer. Retrieved on October 10, 2023. https://www.irrometer.com/sensors.html#wm.
Shultz, J.M., Cohen, M.A., Hermosilla, S., Espinel, Z., & McLean, A. (2016). Disaster risk reduction and sustainable development for small island developing states. Disaster health, 3(1), 32–44. https://doi.org/10.1080/21665044.2016.1173443

World Bank (2022). Water in Agriculture. https://www.worldbank.org/en/topic/water-in-agriculture#1

Figure 18. Dr. Robert Bevacqua (left) showing laterals and other irrigation components for small-scale farming.

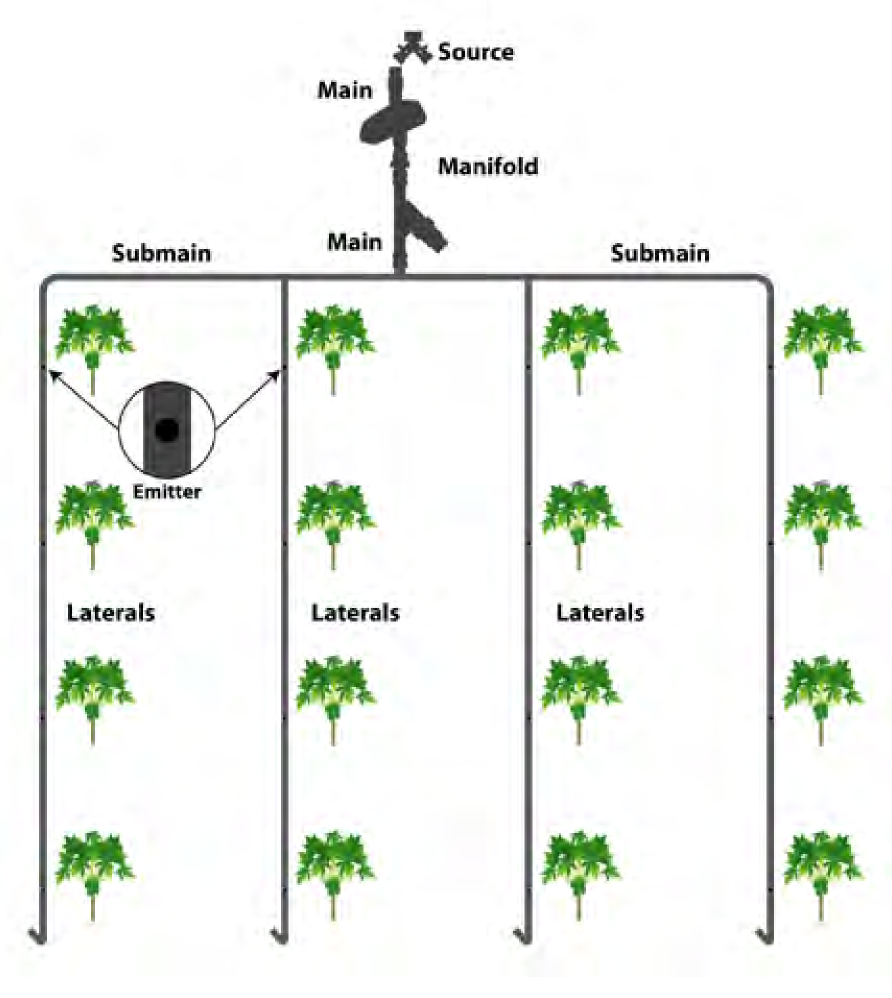

Figure 19. Major components of drip irrigation

PART II: DRIP IRRIGATION SETUP

Drip irrigation is the application of small amounts of water slowly and frequently through emitters or tiny holes spaced along plastic tubes or tape. It is also known as trickle, micro, low volume, or subsurface irrigation.

The advantages of drip irrigation are reduced water use and higher yields due to the precise application of irrigation water. The disadvantages are that drip systems require high-quality water, high installation costs, and certain maintenance skills.

Some factors to consider before acquiring a drip irrigation system are 1) a reliable source of clean water, 2) the water must be pressurized, 3) the field must have good drainage, and 4) the soil depth and texture.

The principal components of a drip system are the water source, a filter, a pressure regulator, a backflow preventer, an injector or siphon, valves, a controller or timer, main lines, submains, and laterals (Figures 18, 19, and 20). The last item, the laterals, are the lines that deliver the water to the base of the plant (Figure 22). The laterals can be tubes with emitters directly inserted into the tube or tubes with thin

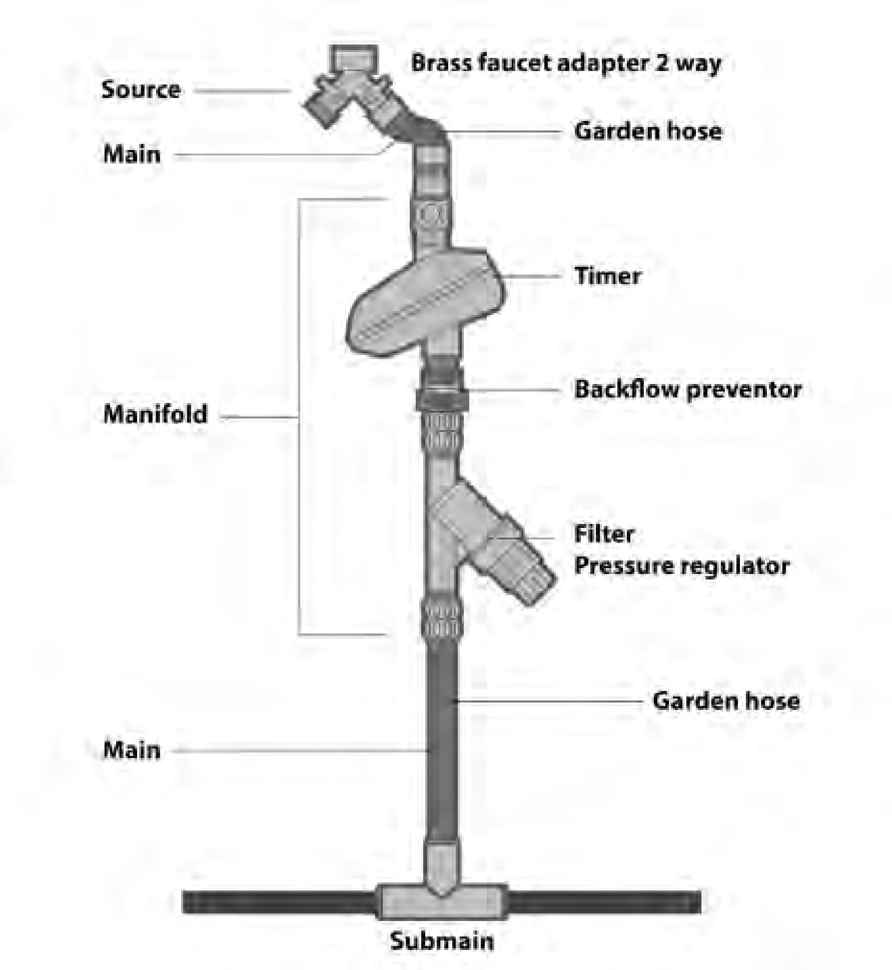

Figure 20. Main and manifold components for a drip irrigation system

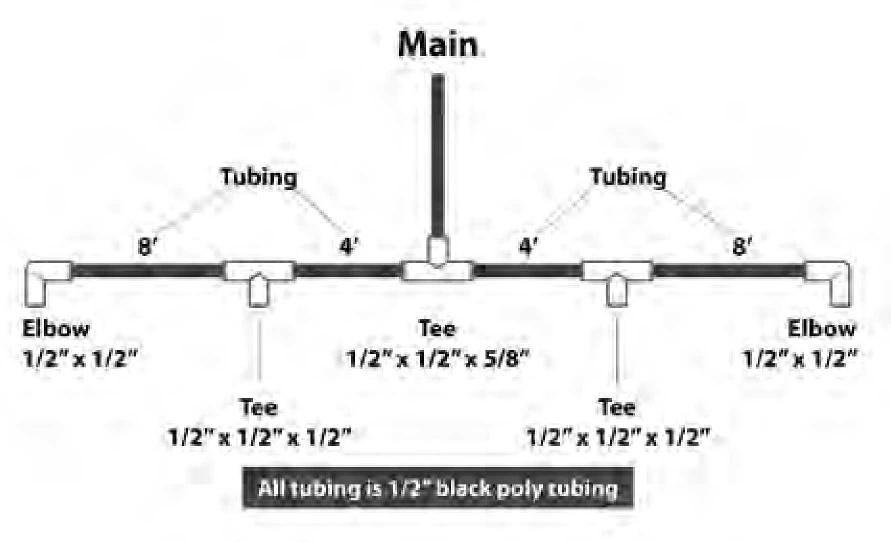

Figure 21. High-pressure water systems often utilize black polyethylene tubing, which is designed to withstand UV light and prevent damage from sun exposure.

"spaghetti" tubing inserted that connects with a mini sprinkler. The laterals can also be taped with spaced holes. No matter the type of lateral, a final component is a means of closing the end of the lateral.

Some components are connected sequentially in an assembly called the "manifold." These components are the filter, pressure regulator, backflow preventer, valve, and controller or timer (Figure 20). The injector or siphon can be a part of the manifold or located separately. A manifold allows for ease of management and troubleshooting.

After assembling a drip system, it is important to flush water through it to remove any materials that may clog the emitters. After flushing, the lateral ends can be closed.

The goal of drip irrigation is to maintain moisture only in the root zone of the crop plants. This means avoiding deep percolation or downward seepage. It also means avoiding horizontal runoff.

In Guam, soil depth is a critical determinant of how much and how often water is applied. In the south, with its deep soil, irrigation can be scheduled two to three times per week with the goal of running the water for one hour to deliver

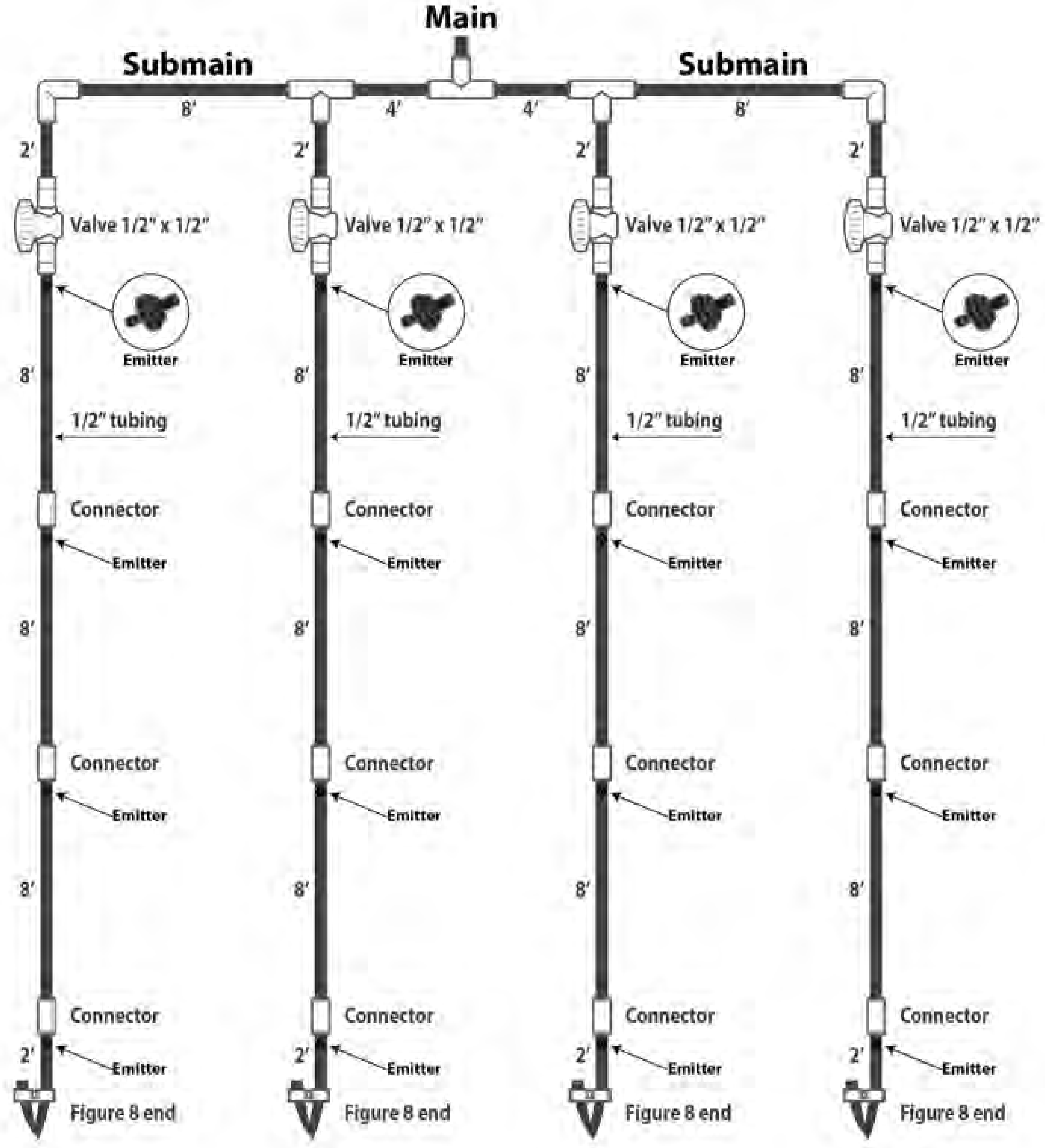

Figure 22. Lateral components for a drip irrigation system

one gallon of water to each plant. With its shallow soil, irrigation can be scheduled two to three times or more per day in the north. Each time running the water for 15 minutes delivers one quart of water to each plant.

A well-maintained drip irrigation system can have a working life of five years. Four maintenance procedures can contribute to a long-life expectancy: filtering, flushing, chlorinating, and acidifying. Filtering is a constant practice. Flushing is a seasonal or trouble-shooting activity. Chlorinating controls algae or other living organisms that may develop in the laterals. Acidifying is used to remove calcium deposits that may clog the emitter holes.

Drip irrigation lends itself to modernization and computerization. In advanced systems, sensors can be installed in the root zone that measures soil moisture. This information can be transmitted to a computer, which sends an electrical signal to the celluloid, opening and closing the valve that turns on or off the water. The advanced systems can be fully automated and deliver the water needed to maintain soil moisture in the root zone.

Drip irrigation also lends itself to injecting agricultural chemicals into the system. Fertilizers and pesticides can be dissolved in water and then metered into the flow of irrigation water via an injector or siphon. The materials are delivered directly into the root zone, where the plant can easily absorb them.

In summary, drip irrigation efficiently applies water slowly and frequently to the root zone of crop plants. In advanced systems, it can be fully automated.

A drip irrigation workshop held on Feb. 18, 2023, at the University of Guam's Yigo Research & Education Center.

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