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Research Article

An Irrigation Scheduling App Based on Evapotranspiration and Effective Rainfall for Bangladeshi Crops

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ABSTRACT

Irrigation management is about determining when and how much water to apply for irrigation. Deciding when to apply irrigation depends on the amount of water the crop uses and the total moisture held in the soil. With rising competition for water and the rational use of natural resources being indispensable, irrigation water management activities must be efficient and accessible to all, not just large-scale farms. We use the Water Balance Approach to compute the optimal irrigation cycle in a smart phone app. Precision irrigation optimizes irrigation and minimizes water use while maximizing crop yields, thereby increasing water resources' effective management. This paper presents a new smartphone app that uses meteorological and soil data to measure water usage to compute a monthly irrigation program for selected crops in Bangladesh. The app calculates the optimal irrigation cycle: the average daily amount of irrigation water in the current month required to maximize crop productivity.

Keywords: Irrigation; Precision farming; Crops; Evapotranspiration; Effective rainfall

INTRODUCTION

This article presents a smartphone-based irrigation app for Bangladesh. Water is supplied to the farmlands as irrigation. The computation of the optimal irrigation schedule depends on crop and soil type as well as environmental factors. How much water needs to be used depends on the available soil moisture and the quantity of water extracted by the crop from the soil. Therefore, irrigation scheduling must consider effective rainfall, soil variables, and plant characteristics (e.g., root zone depth). These factors change throughout the water system cycle. The app computes the optimal water irrigation cycles and water quantities to be applied daily for optimal crop growth in a selected geographic area in the current month. In Bangladesh, May to October is the most humid period. As a result, crops are not subject to water scarcity. The most commonly grown crop between April and October is rice. In contrast, between November and March, Bangladesh experiences a water deficit. This period is best suited for the cultivation of other crops. Optimal water management for crop growth is therefore critical for farmers during this time [1]. The smartphone app presented in this paper uses the Water Balance Approach to optimize the irrigation cycle of selected crops, considering Bangladesh's unique soil and climatic conditions.

MATERIALS AND METHODS

The water balance approach

The water balance approach is instrumental in computing the crop water requirement. It considers the soil as a bucket and advises on the amount of water needed to be put back into the bucket or irrigate. The water demands of plants depend on water inputs such as precipitation (or rainfall) and irrigation and water outputs corresponding to losses such as water Runoff (RO), Deep Percolation (D), and Crop Evapotranspiration (ETc). Deep percolation occurs when the plant roots can no longer absorb water, as the latter is too deep into the soil. The crop root is no longer effective at this depth [2,3]. The surface Runoff (RO) depends on the slope and occurs when the soil's total water holding capacity is exceeded or reached saturation. The excess water will then drain. Crop Evapotranspiration (ETc) contributes to some water loss, particularly in windy and dry weather conditions, as shown in Figure 1 [3]. Irrigation (I) and precipitation (R) or rainfall is deposited in the soil (Equation 1). The soil water balance indicates how much water should be poured into the soil.

Water-based inputs and outputs equation:

$$\Delta S = R - ET_C + I - D - RO \qquad (1)$$

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Where,

ΔS=Change in soil water storage (inches)/differences between inputs (water gain) and outputs (water loss)

R=Rainfall (inches)

ETc=Crop Evapotranspiration (inches)

I=Net Irrigation (inches)

D=Deep Percolation (inches)

RO=Surface Runoff (inches)

Once we removed the water lost due to Deep Percolation (D) and water Surface Runoff (RO), which cannot be used by the plant, we obtain the effective rainfall (Pe), which the plant will use for its growth (Pe=R–D–RO)

Equation (1) becomes Equation (2) if changes in the volume of water (ΔS) are negligible, as in reservoirs, water storage in the soil or aquifers [3,4].

$$I = ET_C - P_e \quad (2)$$

Where,

I=Net Irrigation (inches)

ETc=Crop Evapotranspiration (inches)

Pe=Effective rainfall (inches)

Field Capacity (FC) refers to a soil's capacity to retain water for the plant to grow and varies from one soil to another. The water will first drain off following a heavy rainfall event. As water absorption increases, the residual water is more firmly retained onto the soil particles, making it more difficult for the plant to extract it. While there may still be somewater in the soil, the crop would not absorb sufficient water to meet its needs. The Permanent Wilting Point is reached when the crop can no longer extract the remaining water. The water uptake becomes zero, and the plant becomes wilted. When the water level in the soil decreases below the Permanent Wilting Point (PWP), most plants do not recover even when the soil is re-wetted. At the PWP, plants, crops, or particularly vegetables tend to have a darker or brownish color, and "the plant can no longer draw water from the dried soil and will either die or go into a dormant state" [5]. It is important to note that at the Permanent Wilting Point (PWP), not all of the water is removed from the soil, but the plant cannot extract it.

Total Available Water Capacity (or Available Soil Moisture) is the maximum volume of water a soil can provide to a plant for its growth. It reflects the soil's ability to retain water and make it sufficiently available for plant use [6]. The Available Water Capacity (AWC) (or Available Soil Moisture) is the difference between the water content at Field Capacity (FC), which occurs after all the water has been drained, and the Permanent Wilting Point (PWP) [7]. It is the volume of water, which is accessible to the plant *via* its root system, and stored between the Field Capacity (corresponding to the amount of water remaining in the soil a few days after having been wetted) and the Permanent Wilting Point (PWP), beyond which the plant become limp through heat and loss of water (Figure 2) [7].

Soils with higher Available Water-holding Capacities are more beneficial to plant growth since they can provide sufficient moisture to plants when precipitation does not happen. Coarser soils such as sand or loamy sand hold less water; In contrast, fine heavy soils such as loam and silt retain more water.

The AWC depends on the soil type (Table 1), which can be retrieved from the World Soils Harmonized World Soil Database (available at or the Soil SURvey GeOgraphic database (SSURGO) produced and distributed by the Natural Resources Conservation Service (NRCS) and the National Cartography and Geospatial Center (NCGC). These are available at https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053627. The Kellogg Soil Survey Laboratory (KSSL) also provides pedon data for soil characterization (National Cooperative Soil Survey; 2020) while the USDA provides soil data, but for the US only (https://sdmdataaccess.nrcs.usda. gov/). The app will capture the soil type in the location designated by the app user and retrieved the corresponding AWC (Table 1).

Irrigation is required when the Maximum Allowable Depletion (MAD) of the plant has been reached. The water contained in the root zone should remain above the allowable depletion level. The MAD is usually given as a percentage of the total soil available moisture and is specific to each crop. Our app selected the most common crops (Table 2) cultivated in Bangladesh and retrieved the MAD for each of them. The root zone depth is in feet in Table 2 but converted to inches by the app.

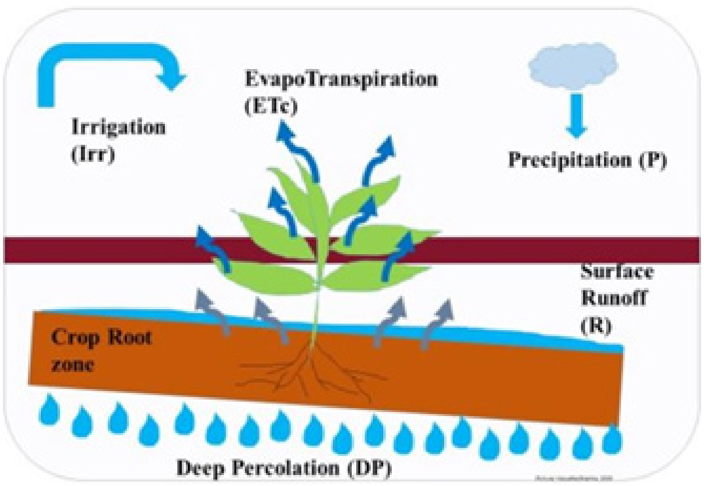

Figure 1: Soil water balance components.

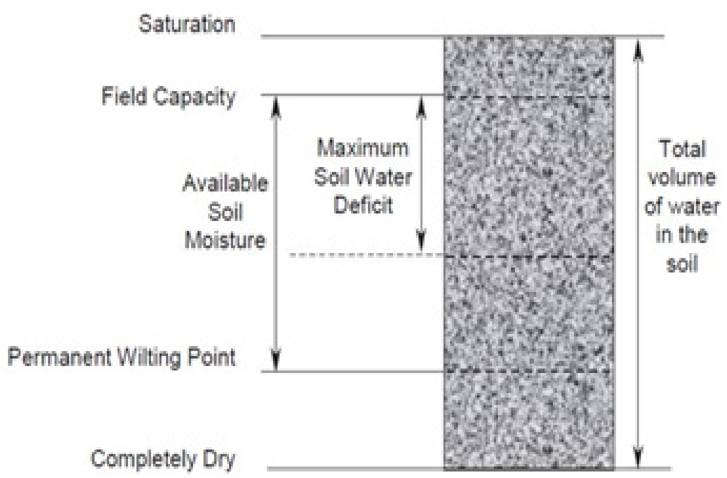

Figure 2: Field capacity, soil moisture, and soil water deficit.

Table 1: Soil water storage capacities [17-19].

Texture class	AWC (inches/inch)
Clay	0.161″
Clay loam	0.17″
Coarse sand	0.046″
Coarse sandy soam	0.114″
Fine sand	0.084″
Fine sandy loam	0.137″
Fine sandy soam	0.098″
Loam	0.183″
Loamy coarse sand	0.083″
Loamy fine sand	0.102″
Loamy sand	0.09″
Sand	0.055″
Sandy clay	0.158″
Sandy clay loam	0.163″
Sandy loam	0.12″
Silt	0.172″
Silt loam	0.179″
Silty clay	0.16″
Silty clay loam	0.165″
Very fine sand	0.123″
Very fine sandy loam	0.2″
Very fine sandy loam	0.166″

Table 2: Crop root zone and MAD for selected Bangladeshi crops [20-23].

Crop	Croproot zone depth (Inches)	MAD (%)
Banana	24	40%
Brinjal/Eggplant	33.6	45%
Cucumber	28.8	48%
Lentil	30	50%
Maize	54	53%
Mustard	18	40%
Oil Palm Fruit	36	65%
Peas green	27.96	38%
Pineapple	18	50%
Potato	23.4	65%
Rice (paddy)	29.4	20%
Seed cotton	53.4	65%
Soybean	33.24	50%
Sugarcane	63	65%
Sweet potato	23.4	65%
Tomato	42	40%
Watermelon	36	43%
Wheat	66	0.55

Evapotranspiration

Crop Evapotranspiration (ETc) measures the amount of water that soils and plants release into the environment. Evapotransporation (ET) sums up both water losses due to soil evaporation and plant transpiration, as moisture is lost through the leaf stomata (i.e., tiny pores on the surface of the leave) after being absorbed by the roots of the plant. For irrigated crops with full ground cover, most of ET is from the leaves' transpiration rather than from evaporation from the soil. When the crop reaches full cover, ET is primarily due to transpiration. Most of the water absorbed by plants is then lost to the atmosphere. That represents about 10 percent of the atmosphere's moisture, with oceans, seas, and other water sources (e.g., lakes, rivers, streams) providing the rest [8]. ET varies according to local weather conditions. Tropical and subtropical, semiarid, and arid climates experience higher water losses due to evaporation rather than transpiration. We retrieved historic evapotranspiration from an existing database. We stored the data into the app so that the user does not have to compute evapotranspiration from cropwat or observations in the field [9]. However, multiple evapotranspiration formulae apply to diverse climate conditions. To compute Crop Evapotranspiration (ETc), we first need to retrieve Reference Evapotranspiration (ETo), which can be done *via* various methods.

Evapotranspiration data sourcing

Retrieving reference evapotranspiration (ETo) is a complex task. In the US alone, the local farming community can refer to local weather forecasting resources such as the Institute of Food and Agricultural Sciences (IFAS) from the University of Florida to retrieve daily and weekly evapotranspiration for Florida (https://fawn.ifas.ufl.edu/tools/et/). In other states, the California Irrigation Management Information System (CIMIS) (available at https://cimis.water.ca.gov/), the high plains regional climatic data center (HPRCC) (available at http://www.hprcc.unl.edu/-Select the state and the automatic weather data station network); the University of Texas (http://www.ce.utexas.edu/prof/maidment/giswr2008/Ex6/Ex6.zip) and the Ag Weather extension from the University of Wisconsin (https://agweather.cals.wisc.edu/sun_water/et_wimn) all provide local evapotranspiration data. Rain Master has retrieved historical evapotranspiration data for every zip code in the United States (http://www.rainmaster.com/historicET.aspx) from nationally recognized weather stations and observation Systems such as NOAA. A 30-year average was computed that gives ET for each month of the year on every zip code. Average monthly evapotranspiration data (mm per day for the selected month) can also be retrieved from GIS systems, as in California [10].

The UC Davis Biometeorology Group provides a list of excel computation sheets that requires data such as temperature, wind speed, number of rainy days, cloud cover, and radiation to compute evapotranspiration data. This computation sheet also applies to non-us locations. Monthly evapotranspiration can be also be retrieved from free open software such as Saga GIS (http://www.saga-gis.org/saga_module_doc/2.1.3/climate_tools_7.html), GRASS GIS (https://grass.osgeo.org/grass78/manuals/topic_evapotranspiration.html), CropWat 8.0, an executable program that requires no additional software to calculate monthly reference evapotranspiration following the guidelines recommended by the ASCE [11,12]. Daily evapotranspiration for any location worldwide using latitude and longitude can also be retrieved from the International Water Management Institute. The Land and Water Division of the FAO have developed software to compute Reference evapotranspiration (ETo) in any location according to FAO standards (http://www.fao.org/land-water/databases-and-software/eto-calculator/en/). Ali et al. (2005) used CROPWAT to provide Monthly Evapotranspiration data (ETo) for different Bangladesh regions. The app retrieves average monthly evapotranspiration ETo (Table 3) for the selected Region.

Crop evapotranspiration

Crop selection: The app user will first select a crop on a list (Figure 3).

Table 3: Reference evapotranspiration (ETo) (inches per day) per geographic region [24].

Months	North Central	North West	South West	North East	South East
Jan	0.090562	0.086712	0.100056	0.093806	0.099746
Feb	0.121543	0.120323	0.130074	0.127444	0.128292
Mar	0.166554	0.171129	0.176972	0.16535	0.163916
Apr	0.189838	0.194446	0.205485	0.175663	0.184736
May	0.180877	0.186777	0.19528	0.168013	0.176087
Jun	0.152664	0.161793	0.155107	0.144689	0.149151
Jul	0.144796	0.148802	0.140443	0.14315	0.13889
Aug	0.148067	0.152438	0.145	0.14614	0.145396
Sep	0.135454	0.13889	0.136649	0.133969	0.139849
Oct	0.130356	0.131833	0.132515	0.129993	0.131791
Nov	0.107948	0.109697	0.111027	0.11092	0.109524
Dec	0.087363	0.087304	0.093174	0.09192	0.093369

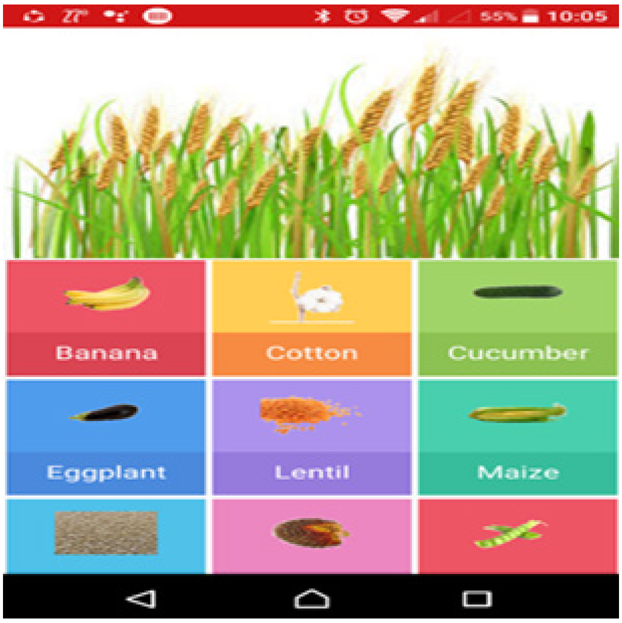

Figure 3: The selection of crop from list of crops.

To compute crop evapotranspiration, we need to multiply the reference evapotranspiration (ETo) (Table 3) by the Crop Coefficient.

Crop coefficients: The crop coefficient (Kc) depends on the crop height, albedo, leaf area, leave conditions, and the canopy resistance.

Kc (dimensionless) depends on the type of crop and crop development stage (Table 4):

- Initial state (Kcini). This stage goes from early planting, germination, and plants' growth to a 10% soil cover. The loss of water is almost entirely caused by soil evaporation.
- Mid-season stage (Kcmid). The Kc hits its peak value during the mid-season. During this time, the crop consumptive water use is the highest.
- End-stage (Kcend). This goes from the start of maturity until full maturity or harvest. The maturity begins with the browning or the yellowing of the fruit or leaves grow in age or sensitivity. The crop coefficient rapidly decreases during the end-stage.

The user will first select the crop growth stage (initial, mid-season, end-stage) (Figure 4), and the app will retrieve the corresponding crop coefficients (Kc) adjusted for the local climatic conditions of Bangladesh (Table 4). In contrast to Doorenbos and Pruitt and Allen et al. [12,13]. list of crop coefficients that apply only to well-managed crops in a sub-humid climate, we retrieved locally calibrated coefficients for a range of selected crops (Table 4) from different sources [14,15].

The app computes the crop evapotranspiration by multiplying local ETo (Table 3) for the selected location (e.g., Bangra in North-West in Figure 5) by the crop coefficient (Kc) (Equation 3). The adjusted reference ET (or ETo multiplied by Kc) is called crop ET (ETc) and corresponds to the crop's water requirements.

RESULTS

Effective rainfall

Now that we have ETc, we need to compute Effective Rainfall (Pe) to obtain I from Equation 2, The portion of rainfall that is not lost, either as surface runoff or as deep percolation, seepage, or evaporation, and is useful for the crop to grow is considered effective. Effective rainfall varies considerably from one location to another. Generally, the more grass is available; the less rainfall is needed because grass absorbs and holds much more moisture than bare ground. On deep-rooted crops, flat ground with little water runoff, or on sandy soils, the effective precipitation is usually around 80% of total rainfall if precipitation occurs regularly and is not very intense. In contrast, high-intensity rain produces much runoff, which is not accessible for the plant to grow. Soils that cannot store moisture, such as heavy soils that contain more clay, will have a greater fraction of precipitation that is ineffective. Steep terrains with a higher rate of water losses due to runoff, thick soils, and areas of high-intensity rainfall will have a much lower effective rainfall, sometimes less than 50% (Figure 6). In countries like India and Pakistan, intensity, frequency, and rainfall are higher in July and August. From November to April, most of the rainfall is effective due to its low intensity, frequency, and amount [16]. In the FAO's Cropwat software, effective rainfall is usually calculated as 80% percent of the total rainfall. Irrigation is needed when there is insufficient effective rainfall to grow crops during that period.

Effective rainfall in Bangladesh

We use the widely accepted USDA Soil Conservation Service (SCS) Method to compute effective rainfall [9,12,17-27].

$$P_e = \frac{P \times (125 - 0.2P)}{125} \qquad \text{For P<=250 mm}$$

$$P_e = 0.1 \times P + 125 \qquad \text{For P>250 mm}$$

Where,

Pe is the monthly effective rainfall (in mm per month).

P is the total monthly rainfall (in mm per month).

We used ARCGIS to retrieve the monthly rainfall in the selected location *via* Advanced Programming Interfaces (APIs).

(https://www.arcgis.com/home/webmap/viewer.html?useExisting=1&layers=e15bf6e4b74b4559a9a3e9ea902a7a57) to compute monthly effective precipitation using the above formula. Alternatively, monthly rainfall is available from sources such as commercial sites (https://www.worldweatheronline.com/developer/api/local-city-town-weather-api.aspx), supranational organizations such as the FAO with CLIMWAT 2.0 for CROPWAT, a joint development of its Water Development and Management Unit and its Climate Change and Bioenergy Unit (http://www.fao.org/land-water/databases-and-software/climwat-for-cropwat/en/), the World Bank (https://datahelpdesk.worldbank.org/knowledgebase/articles/902061-climate-data-api); the International Precipitation Working Group (IPWG), a permanent Working Group of the Coordination Group for Meteorological Satellites (CGMS) (http://ipwg.isac.cnr.it/calval-links.html).

Irrigation cycle

Gross irrigation water requirement: The water required for the crop growth is the net irrigation water requirement (I) in inch/day calculated with Equation 2. The user inputs efficiency of the sprinkler (Figure 7) to transform I into a Gross Irrigation water requirement (GI), which is the amount of water to be used considering water losses since no irrigation system is 100% efficient.

$$GI = \frac{I}{E} = \frac{ET_C - P_e}{E} = \frac{ET_0 K_C - P_e}{E} \quad (4)$$

Where E is the efficiency of the irrigation system in %

Irrigation Runtime (IR): The Irrigation Run Time (IR) is in minutes per irrigation cycle/event depending on the sprinkler Precipitation Rate (PR) (Figure 7). The PR (flow rate per wetted area in inches per hour) is used in Equation 5 to compute IR [2].

The irrigation time (IR in minutes) depends on the rate of precipitation of the sprinkler. The precipitation rate is the volume of water applied over a given area during a specific duration. Inches/hour),

$$R = \frac{(MAD \times TAW)}{PR} \quad (5)$$

Where,

IR is the Irrigation Runtime (in minutes)

MAD is the Maximum Allowable Depletion (in %)

PR is the Precipitation Rate (in inches/hour)

TAW is the Total Available Water (in inches) that represents the volume of water in a soil profile with a known effective rooting depth (Drz).

TAW=AWC × Drz (6)

Where,

AWC is the Soil Available Water Capacity (in inches/inch) as shown in Table 1.

Drz is the root zone depth (Table 2) of the crop (in inches).

Since precipitation rates are per hour, we need to multiple data by 60 minutes.

Irrigation frequency: The Irrigation Frequency (IF) (i.e., number of days between irrigation events) is calculated as follows [2].

$$IF = \frac{(MAD \times TAW)}{GI} \quad (7)$$

Knowing IR and IF, we can then calculate (Equation 8) the Average Daily Irrigation Run time (ADIR) or average minutes of irrigation per day in the current month by dividing IR by the number of days between irrigation events (Figure 8).

Table 4: Crop coefficient factors [25].

Crop	Kcini	Kcmid	Kcend
Banana	1	1.2	1.1
Brinjal/Eggplant	0.6	1.05	0.9
Cucumber	0.6	1	0.75
Lentil	0.4	1.1	0.3
Maize	0.3	1.2	0.5
Mustard	0.7	0.9	0.85
Oil Palm Fruit	0.9	0.95	0.95
Peas green	0.5	1.15	1.1
Pineapple	0.5	0.3	0.3
Potato	0.5	1.15	0.75
Rice (paddy)	1.05	1.2	0.6
Seed cotton	0.35	1.2	0.6
Soybean	0.4	1.15	0.5
Sugarcane	0.4	1.25	0.75
Sweet potato	0.5	1.15	0.65
Tomato	0.6	1.15	0.8
Watermelon	0.4	1.05	0.75
Wheat	0.7	1.15	0.3

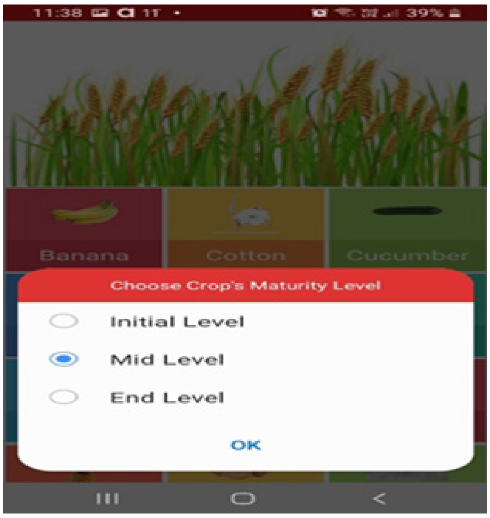

Figure 4: Selection of Crop growth stage.

Figure 5: Selection of location for crop evapotranspiration.

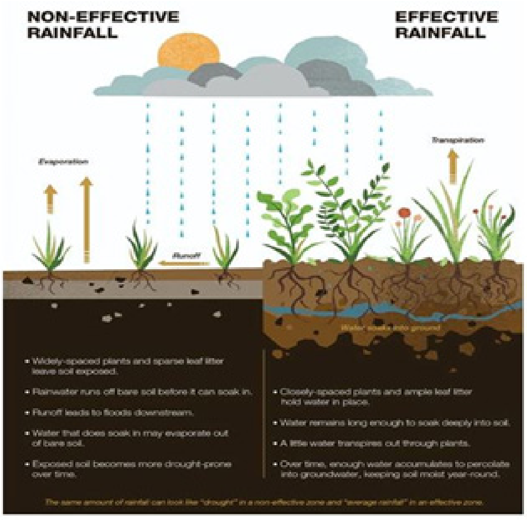

Figure 6: Effective and non-effective rainfall.

Figure 7: Sprinkler efficiency, precipitation rate and monthly rainfall.

Figure 8: Recommended irrigation cycles.

$$ADIR = \frac{IR}{IF} \quad (8)$$

DISCUSSION AND CONCLUSION

The paper presented a new smartphone app, which calculates the optimal daily amount of irrigation water in the current month required to maximize crop productivity in Bangladesh. In order to precisely define an irrigation schedule, we relied on evapotranspiration data, soil and crop characteristics. Such irrigation goals should allow the irrigator to maximize monthly water usage in cultivation. Improvement of water management would raise crop yields while preserving water supplies. In the future, we suggest retrieving reference evapotranspiration from satellite data to simplify the use of the app.

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INSTITUTIONAL REVIEW BOARD STATEMENT

Not Applicable.

INFORMED CONSENT STATEMENT

Not Applicable.

DATA AVAILABILITY STATEMENT

No new data were created or analyzed in this study.

CONFLICTS OF INTEREST

The authors declare no conflict of interests.

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