A smartphone application for irrigation scheduling of crops in northwestern India

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Irrigation management helps determine when and how much water must be applied to irrigate crops. A mobile application (app) has been developed for irrigation scheduling selected crops for the semi-arid and arid regions of Rajasthan, India. These regions experience extreme temperatures in both the summer and winter months, and erratic rainfall conditions. The app uses the water balance approach to compute the most favourable irrigation cycle for a range of crops for selected locations in the state. It also utilizes meteorological, crop and soil data to derive a daily irrigation schedule for the selected month and location.

Keywords: Arid region, evapotranspiration, irrigation management, precision farming, smartphone application.

SITUATED in the northwestern part of India, Rajasthan is the country's largest state (Figure 1). It covers nearly 10.4% (approx. 34.26 Mha) of India's total geographical area. The economy of Rajasthan is primarily agriculture-based, with 66% of the population engaged in agriculture. Farming in the state continues to be majorly rainfed, with more than 60% of the cultivated area in arid and semi-arid tracts[1].

The average yearly rainfall is approximately 575 mm, of which about 532 mm precipitation occurs during the rainy season. However, there is a high fluctuation in rainfall; the annual rainfall in Jaisalmer district can reach 100 mm against 900 mm in the Jhalawar district[2]. Due to scorching summer and heatwaves, Rajasthan reports high potential evapotranspiration (PET) ranging from 2000 mm in Jaisalmer district to 1745 mm in Jaipur. The major soil class is sandy due to poor nitrogen content, low percentage of organic carbon, high infiltration rate and low water-holding capacity. Crops are grown under unfavourable conditions; the probability of drought every other year is 0.5 (ref. 3), while in normal years, farmers experience price decline owing to a market surplus. Several researchers and agencies have reported that crop production in Rajasthan is subjected to various constraints, e.g. poor soil conditions, intermittent drought, fluctuating rainfall, inadequate irrigation infrastructure and depleting groundwater level[4]. The state ranks first in mustard, pearl millet, cumin, cluster beans, coriander and fenugreek production. Rajasthan is the second largest producer of pulses, maize and milk, and the third largest producer of soyabean in India[5].

According to the latest agriculture census (2015–16), the average farm size is 3.07 ha in the state, which is well above the national average of 1.15 ha. Small farmers occupy more than 58.40% of the land of Rajasthan[6]. However, the relatively large average size of landholdings is associated with less fertility, poor soil structure and scarcity of rainfall in most arid and semi-arid areas in Rajasthan. Agriculture and the related sectors accounted for 29.77% of the state's gross value added (GVA) in 2020–21, which is well above the national average GVA of 14.82% (ref. 7).

Surface irrigation is the most common method, which requires a large amount of water and more labour[8]. Unpredictable precipitation and inappropriate water management techniques are two biggest problems in Rajasthan. Studies indicate that irrigation substantially affects agricultural yield and farmer's revenue[9,10]. The complexity of soil–water–crop inter-relationships makes it difficult for farmers to devise their irrigation schedules, but expert models/mobile applications (apps) can assist in irrigation planning. The rising popularity of mobiles and smartphones, and the availability of weather data are conducive to developing smart irrigation apps[11]. The demand for mobile apps in agriculture is growing steadily[12]. Thus, there is a need to develop irrigation scheduling apps for farmers, irrigation specialists, NGOs, farming committees and watershed development agencies.

Smartphone application for irrigation scheduling

Soil water balance approach

The soil water reservoir can be viewed as a water bank with losses and gains[13]. Plant water requirements are determined by considering input and output components of water, as shown in eq. (1). Water inputs or credits include rainfall (R) and irrigation (I), and outputs or debits include losses due to water run-off (RO), deep percolation (D) and evapotranspiration (ETc)[14]. The major variables determining the amount and duration of irrigation are the soil water content and climatic factors such as evapotranspiration and rainfall.

Soil water balance[14]:

$$\Delta S = R - \mathrm{ETc} + I - D - \mathrm{RO}, \tag{1}$$

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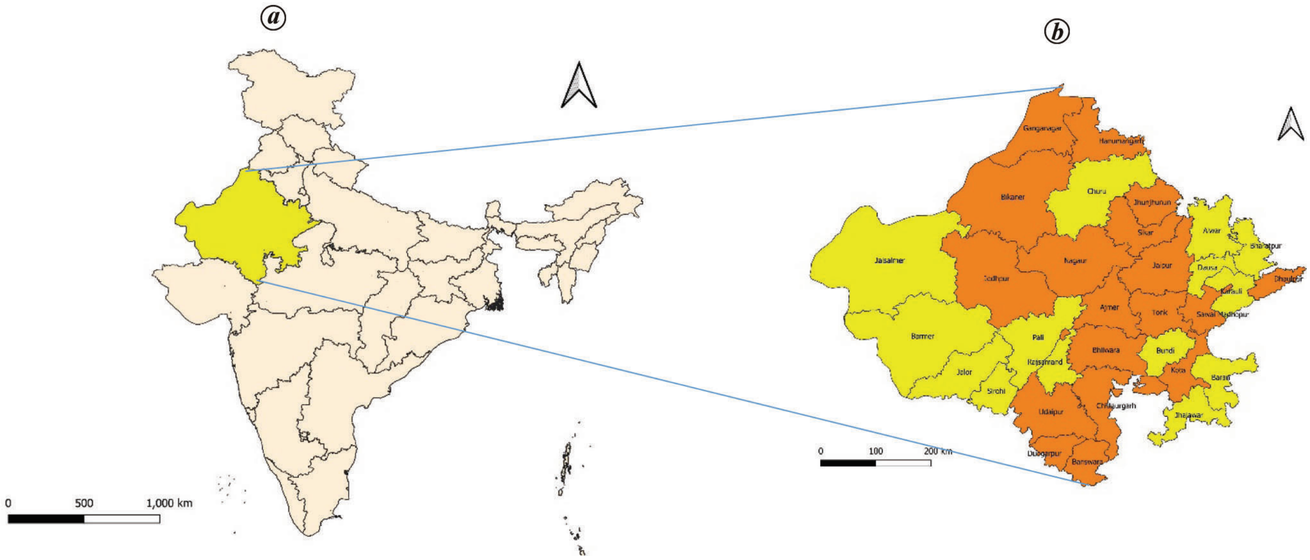

Figure 1. ***a***, Map showing the location of Rajasthan, India. ***b***, Detailed map of Rajasthan and selected locations in the state.

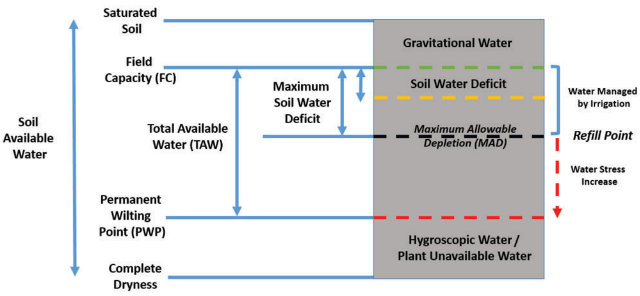

Figure 2. Soil water deficit, field capacity and permanent wilting point.

where ΔS is the change in soil water storage (in)/differences between inputs and outputs, R the rainfall (in), ETc the crop evapotranspiration (in), I the net irrigation (in), D the deep percolation (in) and RO is the surface run-off (in).

Rainfall that is more than the water holding capacity of the plant root zone will run off. That fraction that runs off over the soil surface becomes inaccessible to the crop and does not contribute to its growth. Some rainfall is lost due to deep percolation. This is because the water sinks below the root zone and is no longer available to the crop[14,15].

When there is high rainfall, a significant amount is lost due to deep percolation and run-off. The remaining part ($\mathrm{Pe} = R - D - \mathrm{RO}$) is the effective rainfall (Pe) which is used by the crop for its growth. It is the portion of the precipitation that contributes to crop water requirements. It infiltrates the soil, is stored in the root zone as available water and enables the crop to grow[16]. Net irrigation is the amount of water required for optimal crop growth.

In the soil water balance approach, yearly water storage is null if year-to-year fluctuations are low as in reservoirs and aquifers[14,17]. Thus, the net irrigation requirement equals the difference between crop evapotranspiration and effective rainfall (eq. (2)).

$$I = \mathrm{ETc} - \mathrm{Pe}, \quad (2)$$

where I is the net irrigation (in), ETc the crop evapotranspiration (in) and Pe is the effective rainfall (in).

Plant available water

Field capacity (FC) is the soil moisture content after water has been absorbed by the soil and drained (Figure 2). Sandy soils will drain quickly. In contrast, fine-textured soil such as clay may take several days to drain. A proper irrigation system replenishes the soil until it reaches field capacity. Therefore, net irrigation will bring the moisture level back to field capacity at each irrigation event. The soil water level at field capacity is a good starting point for a water budget system[18].

The permanent wilting point (PWP) is the moisture content of the soil when crops wilt and fail to recover, even if provided with sufficient water (Figure 2). Beyond PWP, the crop starts to wilt. Although there may be water in the soil, the crop cannot to absorb it and will eventually die.

Total available water (TAW) is the water retained in the soil between the field capacity and PWP (Figure 2). According to the USDA-SCS, 2–1 Part 623. *National Engineering Handbook* (1993), total available water (TAW) is the water retained between FC and PWP (Figure 2).

Reference evapotranspiration

Reference evapotranspiration (ETo) occurs from a reference surface (hypothetical grass or alfalfa), with an assumed crop height of 0.12 m and an albedo of 0.23, similar to evapotranspiration from an extensive surface of green grass of uniform height, actively growing, free from any diseases, well-watered and completely covering the ground[19].

Table 1. Average daily reference evapotranspiration for northwestern India (1985–2018)[20]

Region	January	February	March	April	May	June	July	August	September	October	November	December
Arid	0.1123	0.1506	0.1920	0.2479	0.2715	0.2678	0.2151	0.1957	0.2018	0.1874	0.1502	0.1159
Semi-arid	0.1141	0.1489	0.1489	0.1812	0.2195	0.2383	0.1758	0.1593	0.1803	0.1717	0.1458	0.1186
Humid	0.1262	0.1519	0.2034	0.2034	0.2402	0.2380	0.1718	0.1539	0.1754	0.1831	0.1524	0.1291

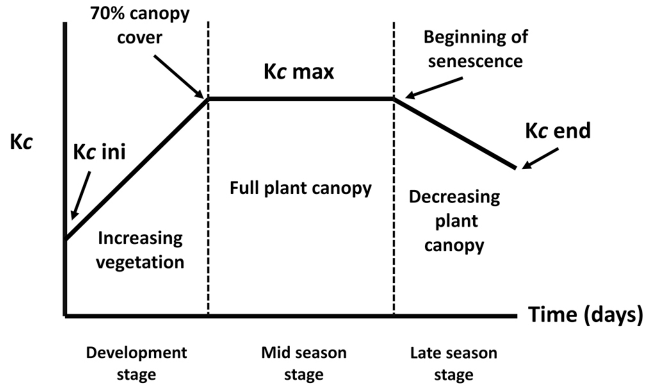

Figure 3. Crop coefficient and crop growth stages.

The Penman–Monteith equation provides the most accurate reference evapotranspiration using radiation data, maximum and minimum temperature, dew point, vapour pressure and wind speed. Evapotranspiration can be estimated using Excel sheets available at http://biomet.ucdavis.edu/Evapotranspiration/PMmonXLS/PMmon.htm.

Reference evapotranspiration can also be obtained from commercial sites (https://developer.awhere.com/), or estimated on-line using software such as HYDRUS 1D (https://www.pc-progress.com/en/Default.aspx?hydrus-1d), or retrieved from the Python package PyETo (https://pyeto.readthedocs.io/en/latest/api.html#evapotranspiration; https://pyeto.readthedocs.io/en/latest/fao56_penman_monteith.html), the R Package Documentation (https://rdrr.io/cran/water/man/dailyET.html), or the R Archive Network (https://cran.r-project.org/web/packages/Evapotranspiration/Evapotranspiration.pdf) or the Davis WeatherLink (https://www.weatherlink.com/).

For smartphone apps, advanced programming interfaces (APIs) that retrieve real-time reference evapotranspiration for any location can be obtained from commercial websites such as SKyWise (http://docs.api.wdtinc.com/skywise-docs/en/latest/api/index.html), Athenium Analytics (https://dev.atheniumanalytics.com/), Meteoblue (https://content.meteoblue.com/en/access-options/meteoblue-weather-api/data-packages), DTN (https://www.dtn.com/sourcing-global-weather-data-for-precision-forecasting-in-the-private-sector/) and aWhere (https://docs.awhere.com/knowledge-base-docs/potential-evapotranspiration-pet/). The developed app stores the average daily reference evapotranspiration computed by Saxena *et al.*[20] for northwestern India. The user can choose a location in one of the main provinces of Rajasthan, and the app retrieves the corresponding daily reference evapotranspiration stored (Table 1).

Evapotranspiration in Rajasthan

During the non-monsoon season, irrigation systems provide water to most of Rajasthan. To maximize output in certain areas, there is irrigation even during the rainy season. Typically, the crop production of irrigation systems is at least double that of rainfed systems[21]. Rajasthan receives ample solar radiation, especially in its western parts. The region's mean bright sunshine duration is 8–8.8 h/day. The normal average annual evapotranspiration is 1701 mm (ref. 22). Most districts in the western arid region of Rajasthan, including Jaisalmer, Nagaur, Bikaner, Jhunjhunu, Ganganagar, Jodhpur Barmer and Churu experience high potential evapotranspiration (PET) during the rainy season[23]. The daily PET requirement of the Thar arid region varies from 2 mm in winter to 12 mm in summer, and between 1500 and 2220 mm per year[24].

The estimated water requirements range from 308 to 411 mm for pearl millet, 244 to 332 mm for cluster beans, 217 to 296 mm for green gram, 173 to 288 mm for wheat and 209 to 343 mm for mustard[25]. It has been reported that a temperature increase of 1% in Rajasthan could increase evapotranspiration by 15 mm, which would translate into an additional water requirement of 34.275 million cubic metres (ref. 26).

Crop evapotranspiration

This is the combination of soil evaporation (or evapotranspirative demand of the atmosphere) and plant transpiration (i.e. evaporation of water from the plants) (https://wwd.ca.gov/wp-content/uploads/2015/09/water-management-handbook-2013.pdf). Usually, evaporation from the soil accounts for about 10% of crop evapotranspiration. Plant transpiration accounts for the remaining 90% (ref. 8). Most of the water is lost through evaporation in the early stages of crop growth. When the plant reaches maturity, most of the water is lost through transpiration[27].

Crop evapotranspiration rate varies significantly among plant species. According to the ASCE Manuals and Reports on Engineering Practice No. 70 (2015), crop coefficients (K_c) also vary with the crop growth stage (Figure 3). In addition, cultivation practices and local climatic conditions in crop development patterns can affect the crop coefficients[28].

Table 2 shows crop coefficients for selected Indian crops to estimate crop water requirements under tropical climatic conditions[29].

The actual crop evapotranspiration (ETc) for the selected crops is obtained by multiplying the reference evapotranspiration (ETo) by the crop coefficient (K_c) for the selected crop. The user selects the crop (Figure 4 *a*) and its growth stage (Figure 4 *b*), and the app retrieves the corresponding crop coefficient to compute ETc.

$$\text{ETc} = \text{ETo} * K_c,$$

where ETc is the crop evapotranspiration (in), ETo the reference evapotranspiration (in), K_c is the crop coefficient (dimensionless crop-specific coefficient).

Effective rainfall

Effective rainfall is measured locally using several field techniques. These include the drum technique for rice, lysimeters and the Ramdas method[30]. Effective rainfall is normally computed as a fraction of the monthly/weekly/daily precipitation minus a locally calibrated water volume reduction. The reduction depends on local environmental conditions that vary with topography and soil type.

FAO methods

Monthly effective rainfall: Effective rainfall is usually computed as a fixed percentage or a fraction of the total monthly rainfall minus a locally calibrated water volume reduction. For crops other than rice, effective rainfall is usually calculated as 70% of the average rainfall in the current season. Else, effective rainfall is the lowest amount of monsoon rainfall occurring in three out of four years[30]. For rice, total rainfall varying from 50% to 80% is considered effective. According to Brouwer and Heibloem[31], the following equation may be used to estimate monthly Pe in areas where the slope does not exceed 4%–5%.

$$\text{Pe} = 0 \quad \text{when } P \leq 12.5 \text{ mm},$$

$$\text{Pe} = 0.6\,P - 10 \quad \text{when } 12.5 \text{ mm} < P \leq 75 \text{ mm},$$

$$\text{Pe} = 0.8\,P - 25 \quad \text{when } P > 75 \text{ mm}.$$

where Pe is the effective monthly precipitation (mm) and P is the total monthly precipitation (mm).

Effective precipitation during the Indian monsoon season from June to September can also be estimated using the following formula[32]:

$$\text{Pe} = 0.8 * P \text{ for rice paddy},$$

$$\text{Pe} = 0.7 * P \text{ for non-paddy crops},$$

where Pe is the effective monthly rainfall (mm) and P is the total monthly rainfall (mm).

Effective rainfall is reduced to zero during the rest of the year because significant rainfall does not occur regularly[32].

In the first version of the app (monthly irrigation cycle) that computes the average irrigation runtime per day for the current month, the user enters monthly precipitation (Figure 4 *c*) and the app automatically calculates the effective monthly rainfall using the Brouwer and Heibloem formula. The user can retrieve monthly rainfall for any location in India from https://www.arcgis.com/home/item.html?id=e6ab693056a9465cbc3b26414f0ddd2c. Alternatively, the app can retrieve rainfall from the World Bank climate data using API (https://datahelpdesk.worldbank.org/knowledgebase/articles/902061-climate-data-api). Accuweather also provides a monthly precipitation forecast (daily rainfall for the next 30 days). The user must click on a specific day of the month, scroll down to obtain daily water quantity (in), and add them up to compute monthly precipitation (https://www.accuweather.com/en/in/new-delhi/187745/daily-weather-forecast/187745?day=2). Alternatively, one can retrieve 15-day forecast precipitation from the same site (https://www.accuweather.com/en/in/new-delhi/187745/weather-forecast/187745) to compute the rainfall of the current month.

Therefore, we can use either current or forecasted precipitation to compute the optimal irrigation cycle for the current or upcoming month.

Monthly and decadal effective precipitation: The generic USDA Soil Conservation Service formula is used to compute monthly and decadal effective precipitation[33,34].

For monthly effective rainfall:

$$\text{Pe} = P * (125 - 0.2 * P)/125 \quad \text{for } P \leq 250 \text{ mm},$$

$$\text{Pe} = 125 + 0.1 * P \quad \text{for } P > 250 \text{ mm},$$

where Pe is the effective monthly rainfall (mm/month) and P is the total monthly rainfall (mm/month).

For decadal effective rainfall:

$$\text{Pe(dec)} = P\text{dec} * (125 - 0.6 * P\text{dec})/125 \quad \text{for } P\text{dec} \leq (250/3) \text{ mm},$$

Table 2. Crop coefficients for selected crops[41–43]

	K_c value		
Crop	Development	Mid	Late
Clover	0.76	0.965	1.24
Maize	0.55	1.23	0.64
Onion	0.52	1.04	0.87
Potato	0.42	1.257	0.57
Rice	1.12	1.24	0.97
Sunflower	0.64	1.23	0.39
Wheat	0.33	1.08	0.64
Bell pepper	0.6	1.05	0.90

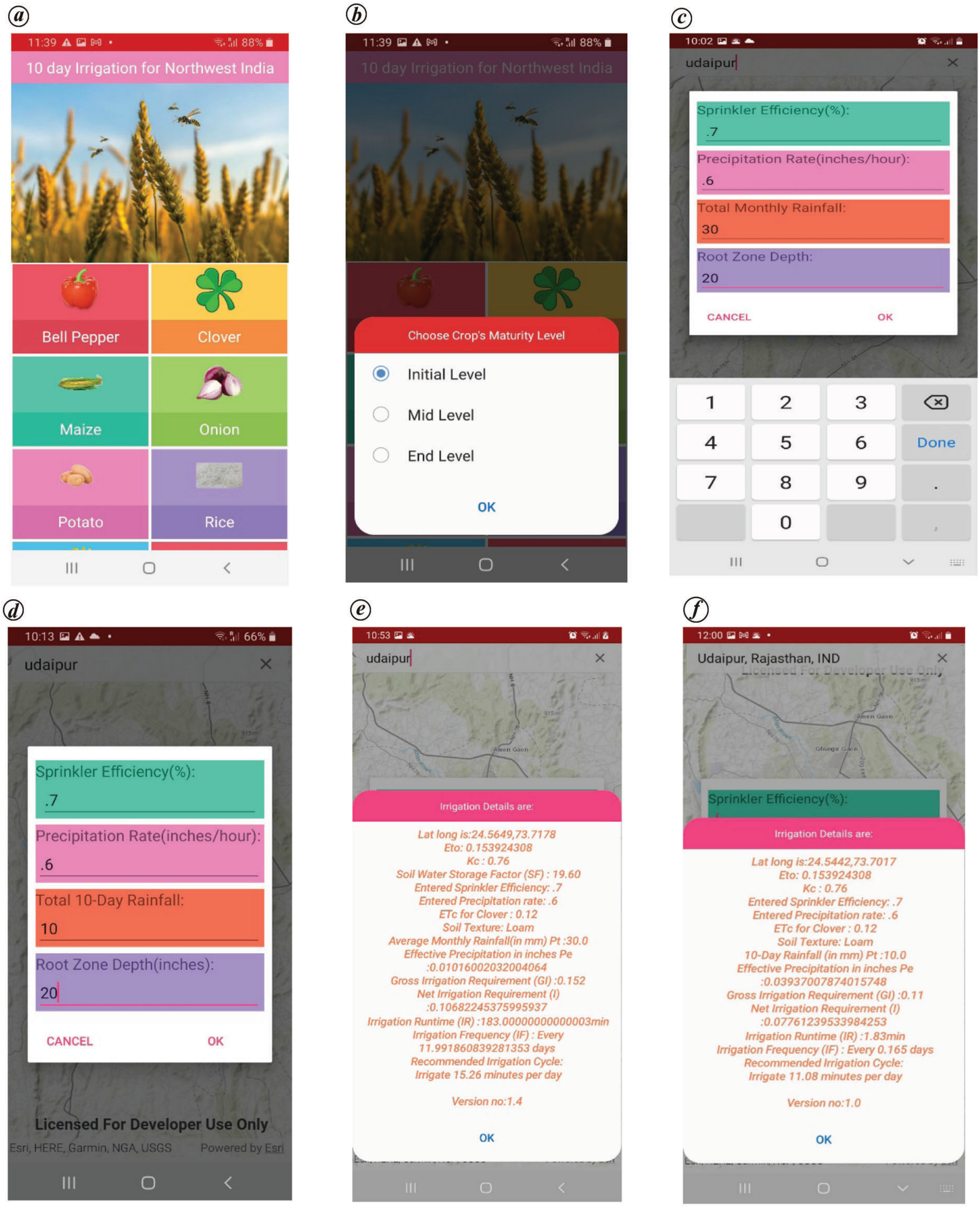

Figure 4. Screenshots of different user interface of the developed mobile app. ***a***, Crop selection. ***b***, Crop growth stage. ***c***, User data input with monthly rainfall. ***d***, User data input with 10-day rainfall. ***e***, Monthly irrigation cycle. ***f***, Ten-day irrigation cycle.

$$Pe(dec) = (125/3) + 0.1 * P\mathrm{dec} \quad \text{for } P\mathrm{dec} > (250/3) \text{ mm},$$

where Pe(dec) is the effective decadal rainfall (mm/10-day period) and *P*dec is the total decadal rainfall (mm/10-day period).

Alternatively, the Indian-2 method recommends that rainfall less than 0.25 in (6.25 mm) on any day be treated as ineffective. Rainfall over 3 in (75 mm) per day and above 5 in (125 mm) in 10 days is ineffective[35].

For daily case:

$$\mathrm{Pe} = 0 \quad \text{when } P < 6.25 \text{ mm},$$

$$\mathrm{Pe} = P \quad \text{when } 6.25 < P \leq 75,$$

$$\mathrm{Pe} = P - (P - 75) \quad \text{when } P > 75,$$

where Pe is the effective daily rainfall (mm/month) and *P* is the total daily rainfall (mm/month).

For 10 days:

$$\mathrm{Pe} = P \quad \text{when } P \leq 125 \text{ mm},$$

$$\mathrm{Pe} = P - (P - 125) \quad \text{when } P > 125 \text{ mm},$$

where Pe is the effective decadal rainfall (mm/10-day period) and *P* is the total decadal rainfall (mm/10-day period).

We have developed a decadal app (decadal irrigation app) that computes the average recommended irrigation cycle over ten days using the aforementioned Indian-2 method. The app calculates Pe over ten days. Ten-day rainfall data are provided by the user without instrumentation in the field (Figure 4 *d*), and the app automatically computes the effective rainfall for that period. Alternatively, 10-day rainfall can be retrieved from any GIS system that provides APIs for developers.

Computation of irrigation cycle

Net irrigation requirement: Net irrigation requirement (*I*) for the selected crops of the irrigated area can be computed by subtracting the crop evapotranspiration from the effective rainfall

$$I = \mathrm{ETc} - \mathrm{Pe},$$

where *I* is the net irrigation requirement (in/day), ETc the crop evapotranspiration (in/day) and Pe is the effective rainfall (in/day).

Irrigation is not required if *I* is negative (or Pe > ETc).

Gross irrigation requirement: The app computes the gross irrigation (GI) requirement (eq. (3)). Then, the user provides the sprinkler efficiency (*E*) rate (Figure 4 *d*). This factors in irrigation system losses due to wind drift and evaporation due to the crop, soil and sprinkler type.

$$\mathrm{GI} = \frac{I}{E} = \frac{\mathrm{ETc} - \mathrm{Pe}}{E} = \frac{\mathrm{ET}_0 K_c - \mathrm{Pe}}{E}, \quad (3)$$

where *E* is the efficiency of the irrigation system (%) and is provided by the user, *I* the net irrigation requirement (in/day), ETc the crop evapotranspiration (in/day) and Pe is the effective rainfall (in/day).

Irrigation run time: Next, irrigation run time (IR) is calculated (i.e. the sprinkler total watering time) per cycle/event[36,37]. The precipitation rate of the irrigation system (PR; in/h) measures the rate at which an irrigation system applies water to an area per unit of time, and is provided

Table 3. Maximum allowable depletion (MAD) for selected crops[39,44]

Crop	MAD
Clover	0.50
Maize	0.52
Onion	0.30
Potato	0.65
Rice	0.20
Sunflower	0.45
Wheat	0.55
Bell pepper	0.30

Table 4. Available water-holding capacity (AWC) by soil texture class[18,44,45]

Texture class	AWC (in/in)	AWC (in/ft)
Clay	0.161	1.94
Clay loam	0.170	2.05
Coarse sand	0.046	0.56
Coarse sandy loam	0.114	1.37
Fine sand	0.084	1.01
Fine sandy loam	0.137	1.65
Fine sandy loam	0.098	1.18
Loam	0.183	2.20
Loamy coarse sand	0.083	1
Loamy fine sand	0.102	1.23
Loamy sand	0.09	1.08
Light clay	0.175	2.1
Sand	0.055	0.67
Sandy clay	0.158	1.9
Sandy clay loam	0.163	1.96
Sandy loam	0.12	1.44
Silt	0.172	2.07
Silt loam	0.179	2.15
Silty clay	0.160	1.93
Silty clay loam	0.165	1.99
Very fine sand	0.123	1.48
Very fine sandy loam	0.20	2.5
Very fine sandy loam	0.166	2

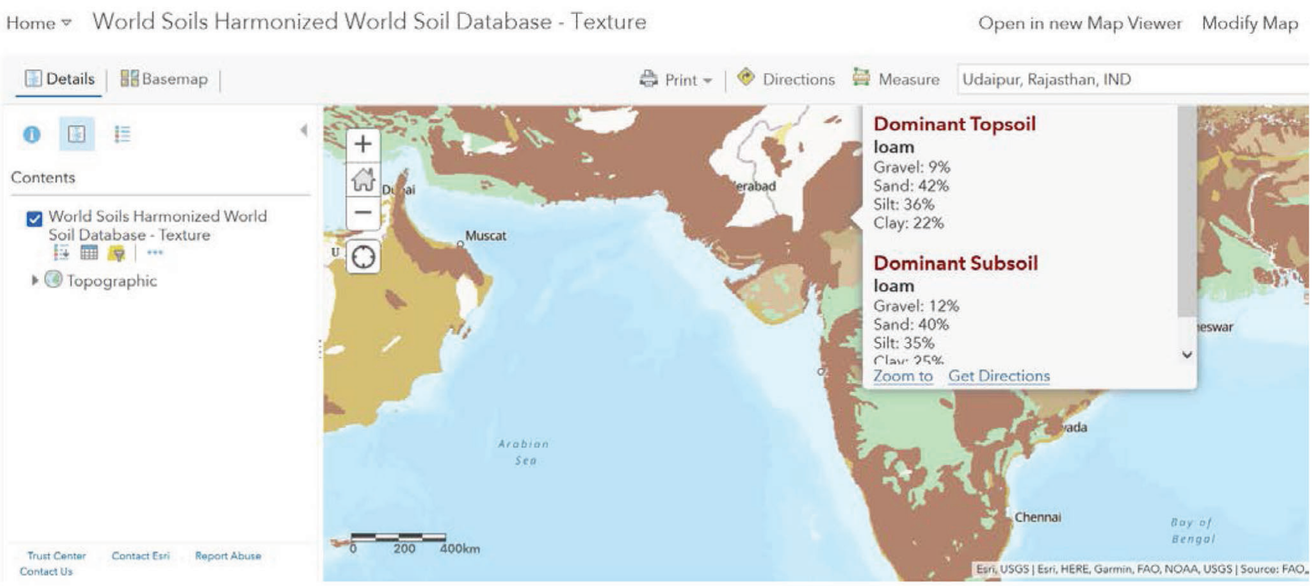

Figure 5. Soil texture for selected locations in northwestern India.

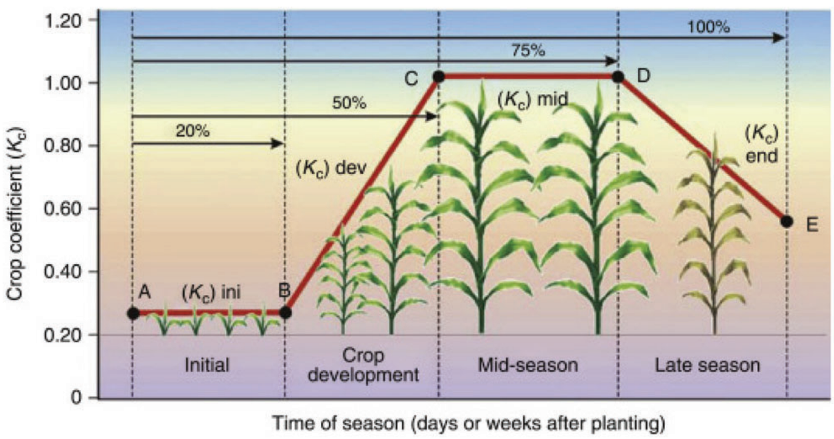

Figure 6. Crop growth stages and root zone depth[46].

by the user (Figure 4 *d*). The application rate is used to calculate IR as follows

$$\mathrm{IR} = \frac{\mathrm{MAD} \times \mathrm{TAW}}{\mathrm{PR}}, \tag{4}$$

where MAD is the maximum allowable depletion below which plants become stressed (Figure 2). The value of MAD increases during the crop growth period as roots grow deeper and the crops need more water. The MAD value is expressed as a percentage. Table 3 shows typical MAD values for the selected crops.

$$\mathrm{TAW} = \mathrm{AWC} \times D_{\mathrm{rz}}, \tag{5}$$

where TAW is the total available water for a crop with an effective root zone depth of D_{rz} in the selected location. TAW or reservoir capacity is obtained by multiplying the soil available water holding capacity (AWC) (in/in) by the effective root zone depth (D_{rz}; in) of the selected crops[18] (eq. (5)) (Table 4).

AWC is the available water-storage capacity of the soil corresponding to the amount of water that the soil can hold. The soil water storage capacity depends on the combined storage capabilities of the different layers and types of soil. The app retrieves the soil texture from the Harmonized World Soil Database (HWSD) (Figure 5) and the corresponding AWC (Table 4) for the selected location to compute TAW.

The effective crop rooting depth is the depth to which the crop extracts most of the water[38]. It varies with the crop type and development stage[39]. Therefore, rooting depth affects the amount of water accessible to the crop and the amount used between irrigation events. The effective crop rooting depth is provided by the user (Figure 4 *d*) and varies with the crop development stage (Figure 6). Alternatively, the effective root depth can be retrieved from the literature[19,40].

We multiply IR by 60 min since precipitation rates are per hour.

Irrigation frequency: The irrigation frequency (IF; days) i.e. the number of days between irrigation events is calculated as follows[37].

$$\mathrm{IF} = \frac{\mathrm{MAD} \times \mathrm{TAW}}{\mathrm{GI}}, \quad (6)$$

where MAD is the maximum allowable depletion (dimensionless), TAW the total available water (in) and GI is the gross irrigation requirement (in/h).

Knowing IR and IF, we can calculate the daily irrigation run time (minutes of irrigation per day) for the month (Figure 4 *e*) and week (Figure 4 *f*).

Conclusion

The primary uses for the developed app are not just farmers, but the community agriculture as a whole. Local NGOs, farmer's associations and rural municipalities could be likely users if individual farmers do not have internet access. The agribusiness sector can use this app to optimize irrigation scheduling in large areas potential savings with higher. It will supplement existing tools (e.g. lysimeters, visual evaluation, etc.) that farmers use to assess the optimal irrigation timing. The app could be extended to other locations with adequate effective rainfall formula or to other crops with appropriate crop coefficient factors. We plan to extend the algorithm for other states when APIs to retrieve evapotranspiration are available in them. Finally, the development of this app paves the way for a new research stream for precision farming in India.

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ACKNOWLEDGEMENT. The authors thank Supriya Shah for developing the app.

Received 8 September 2021; revised accepted 18 July 2022

doi: 10.18520/cs/v123/i7/865-873