Chapter 4

On the Use of Decision-Support Tools for Improved Irrigation Management: AquaCrop-Based Applications

Joost Wellens, Dirk Raes and Bernard Tychon

Additional information is available at the end of the chapter

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Abstract

Feeding more people with less water is putting efficient irrigation practices worldwide high on the agendas. As a reaction, over the last decades, numerous irrigation decision-support tools have been developed. For several reasons, the gap between farmer and modeler remained in most cases too large. The Food and Agriculture Organization of the United Nations (FAO) contributes to alleviate the encountered adoption limitations with AquaCrop and its stand-alone AquaCrop plug-in. This simple and robust field-crop-water balance has been successfully tested for a wide range of crops and regions, and its database is still expanding through worldwide contributions. The present chapter describes how AquaCrop can help irrigation advisory services draft efficient irrigation calendars that are easily applicable and adoptable: either by the elaboration of site-specific irrigation schedule calendars in chart format when the user has no access to the needed data or by the integration of its plug-in in a server/client ICT application offering centralized data management. As for the irrigation charts, studies prove 10-30% water savings, while maintaining yield and requiring minimum data. The server/client application offers an all-in advice tool, including real-time irrigation advice and yield forecasts. No adoption assessments have yet been carried out, but several ongoing pilot studies are promising.

Keywords: irrigation advisory service, decision-support tools, AquaCrop model, water-use efficiency, irrigation charts, ICT

1. Introduction

Irrigation is worldwide being considered as one of the means to increase or secure food production. As a result, in many parts of the world, the pressure on the available water resources has also intensified and is facing its limits. The challenge for the next decades will be how to feed ever more people with ever less water resources. The management of irrigation systems is, in most cases, based on the farmer's experience instead of rational basis (use of agro-climatic data) [1, 2]). The inefficiencies detected in the irrigation process [3, 4] have driven the development of tools to facilitate farmers the irrigation scheduling. Stakeholders need practical decision-support tools to help them assess irrigation practices and the resulting yield. Simulation models provide a low-cost means of investigating a wide range of management options.

Despite the plethora of irrigation scheduling support systems that have been developed over the past decades, there is little evidence of widespread adoption by farmers [2, 5]. Most producers find state of art irrigation scheduling tools overwhelming and lack the skills necessary to install, operate and troubleshoot them [1, 6]. Often not all required data are available at parcel level (real-time climate data and soil characteristics) or crops are not (yet) taken into account by the irrigation advice service [7]. Or the variables provided (e.g., daily crop water requirements) require additional calculations to transform it into useful data, namely management variables (e.g., daily irrigation time) [2]. Still another explanation for the low adoption rate is that farmers are not confident whether their use would actually transform into benefits [6, 8, 9]. This chapter presents some promising results and perspectives to bridge the gap between farmers and modelers, and overcome the above-stated limitations. The approach helps irrigation advisory services in the elaboration of efficient irrigation calendars that can be easily used by farmers, profiting hence to advisers and producers.

The Food and Agriculture Organization of the United Nations (FAO) has developed AquaCrop, a field-crop-water-productivity simulation model for use as a decision-support tool in planning and analysis [10, 11]. Being a water-driven crop model, crop biomass and harvestable yield are simulated in response to available water (soil moisture and irrigation). Although constructed upon basic and complex biophysical processes, only a relative small number of parameters are needed to adapt AquaCrop to different cases and crops. Often the integrated default input variables are sufficient and do not require additional fitting. When additional variables are needed, they are mostly intuitive and can easily be determined using simple methods [10, 12].

AquaCrop has been broadly tested for different corps around the world under diverse environments: for example, barley in sub-Saharan Africa [13], wheat in Iran [14] and in western Canada [15], teff in Ethiopia [16], quinoa in Bolivia [17] and maize in California [11]. Freely downloadable at FAO's website, the model contains a default database of the world's major crops (cotton, maize, potato, quinoa, rice, soybean, sugar beet, sunflower, tomato, wheat, barley, sugar cane, sorghum and teff [18]), and the list of crops is ever growing due to worldwide contributions. It has also been used to design different deficit irrigation strategies [19], to evaluate sowing strategies in a semiarid environment [20] and to develop an economic model for decision-support system at the farm scale [21]. An open source and animated Zotero Internet forum maintains an updated list of all peer-reviewed journal papers and Ph.D. manuscripts published on the calibrations and applications of the AquaCrop model [22].

How easily significant water savings can be obtained based on AquaCrop-derived simulation results is presented further down based on a case study in Burkina Faso. However, a quick literature review yields ample examples on the benefits of irrigation advice services. Water savings, while maintaining the same yield, can reach from 10 to 30% when compared with water use recorded in previous irrigation seasons without irrigation advice [1, 2, 8]. Other examples managed to combine yield increase and water-use reduction; for example, Eching [23] indicated an 8% yield increase with a 13% water-use reduction. The operating costs for an irrigation advisory service in Spain, including several field visits from technicians, are estimated at about 3 € ha^{-1} $year^{-1}$ [7]. Lorite et al. [25] studied the average annual irrigation benefits of shifting to irrigation advisory services ranging from 100 € ha^{-1} (for wheat and maize) to more than 400 € ha^{-1} (for sugar beet, sunflower and olive). Unfortunately, benefit assessments on irrigation advisory services are rare. The few existing financial studies confirm irrigation scheduling services are highly profitable [24] and encourage the integration of economic indicators in order to contribute toward a greater acceptance of advisory services [25].

The actual used irrigation advice methods and tools can be grouped into two approaches: the one using long-term averages and the other based on real-time data. The real-time approach requires access to daily weather data in conjunction with water budget calculators or crop models that rerun and update their output each time new data are available. The long-term averages approach is less complicated and does not require access to daily weather data (apart from rainfall, if applicable) [8]. For a given climate and crop, an irrigation calendar or different irrigation scenarios are elaborated only once and stuck throughout the growing season. AquaCrop and AquaCrop plug-in [26], a stand-alone executable deprived of its graphical user interface but offering all the same possibilities as the full program, offer the possibilities to play on both fronts.

2. Model description

FAO developed and freely distributes the AquaCrop model. This dynamic crop-growth model predicts yield response to water; it assumes a linear relationship between biomass (*B*) growth rate and crop transpiration (*Tr*). Only a small amount of water taken by the roots is used for growth and metabolism (i.e., biomass), the remaining is lost by transpiration. The transpiration rate depends directly on the available soil moisture; as more water depletes, *Tr* becomes less than potential, and biomass growth will reduce. For more details on the water and other stress mechanisms, refer also the studies of Steduto et al. [30]. In AquaCrop, actual crop transpiration is translated into biomass through a water productivity (*WP*) parameter. For a given time interval, the accumulated biomass is a result of the *WP* and the accumulated canopy transpiration: $B = WP \times \Sigma Tr$ [27–29]. The *WP* defines the amount of biomass a crop can produce per unit of water consumed. It is a crop-specific parameter. When normalized for atmospheric evaporative demand, $WP^* = B/\Sigma(Tr/ETo)$, it remains virtually constant over a range of environments [29] in order to make AquaCrop applicable across diverse locations and seasons. For most crops, only part of the biomass produced is partitioned to the harvested organs to give yield. The harvestable yield (*Y*) is portioned from the biomass by means of another crop-specific parameter known as the harvest index (*HI*): $Y = \text{HI} \times \text{B}$. The model does not include underlying hierarchical processes simulating the intermediary steps leading to biomass accumulation. As a consequence, the model structure is simple with few input parameters [10]. The model uses the more easily obtainable canopy ground cover (*CC*, the fractional coverage of the soil by the canopy) instead of leaf area index (*LAI*) as the basis for calculating transpiration and monitoring crop development.

AquaCrop uses two different kinds of parameters: (i) fixed or conservative parameters and (ii) case-specific or nonconservative parameters. Conservative parameters are independent of geographical region, management techniques or time. They should be determined under non-limiting growing conditions but remain valid for stress conditions through the integration of stress response functions [10, 12]. These conservative parameters consist mainly of canopy cover growth (*CGC*) and decline (*CDC*); crop coefficient for transpiration at full canopy (K_c); *WP* for biomass; and soil water depletion thresholds. These parameters are applicable to a wide range of different conditions and crop cultivars [30]. Some other crop parameters are case-specific and nonconservative (e.g., sowing density, length of phenological stages). Nonconservative parameters are affected by climate, field practices and soil conditions. The operator needs to provide them for each specific case and cannot apply them broadly. If not available, the model can offer estimations [12, 31]. FAO has calibrated crop parameters for several crops and provides them as default values in the crop files stored in the AquaCrop database. At the same time, literature on supplemental crops keeps growing.

New crops can be added to the database or an existing crop tested for a new agro-climatological region. In a first step, the calibration and validation procedure mainly bases on the monitoring of the fractional canopy cover evolution. **Figure 1** shows how the evolution of the fractional canopy cover can be followed by taking overhead pictures of the canopy throughout the growing season and quantified by means of image analysis software (e.g., [32]). Once the evolution of the fractional canopy cover is plotted (*CC*), the most important crop characteristics can be derived from this curve: days to emergence and maturity, canopy growth coefficient (*CGC*), canopy decline coefficient (*CDC*), etc. In a second step, *WP* and *HI* can be fine-tuned in order to match at best simulated versus observed yield.

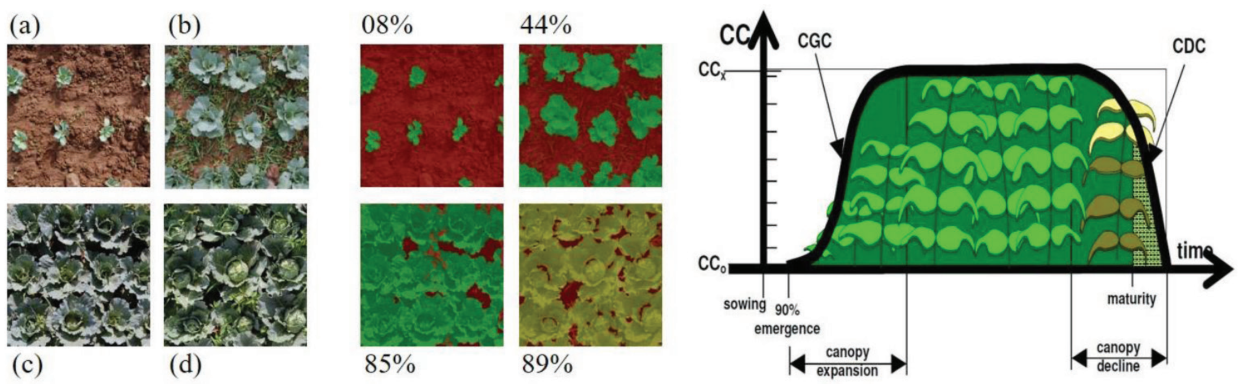

Figure 1. Left (a-d): overhead pictures of a cabbage field in Burkina Faso; middle: derived fractional cover data using image analysis software [32]. Right: canopy cover (CC) development curve and most important crop parameters [31] (CC_o: initial canopy cover; CC_x: maximum canopy cover; *CGC*: canopy growth coefficient; *CDC*: canopy decline coefficient).

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For each day of the simulation period, AquaCrop requires minimum and maximum air temperature, reference evapotranspiration as a measure of the evaporative demand of the atmosphere and rainfall. Additionally, the mean annual CO_2 concentration has to be known (AquaCrop provides an historical time series of mean annual atmospheric CO_2 concentrations measured at Mauna Loa Observatory in Hawaii). The needed soil hydraulic characteristics, describing the soil water retention and soil water movement in the soil, are as follows: (i) the hydraulic conductivity at saturation: the ease with which water moves through a completely wetted soil; (ii) the soil water contents at saturation: the soil is completely filled with water and there is no air left; (iii) field capacity: the amount of soil moisture after excess water has drained away and (iv) permanent wilting point: the minimum soil moisture at which a plant wilts. One can either make use of the indicative values provided by the model for various soil texture classes or import locally determined data.

When all data are available (measured, estimated or adapted), AquaCrop offers the possibility to (i) determine net irrigation requirements in a given environment; (ii) assess an existing irrigation schedule and (iii) in the framework of the present chapter, to generate an irrigation schedule according to specified criteria. To generate an irrigation schedule for evaluating or planning a particular irrigation strategy, the irrigation method (sprinkler, drip or surface, which determines the fraction of the soil surface wetted by irrigation), and the time and depth criteria have to be specified. Time and depth criteria used for the generation of irrigation schedules are listed in **Table 1** [33].

	Parameter
Time criterion	
Fixed interval (days)	Time interval between irrigations (e.g., 10 days).
Allowable depletion (mm water)	Amount of water that depletes from the root zone (the reference is soil water content at field capacity) until irrigation is needed (e.g., 30 mm).
Allowable depletion (% of RAW)	Percentage of RAW that depletes until irrigation is needed (e.g., 100%).
Depth criterion	
Back to field capacity (± extra mm water)	Extra water on top of the required dose to bring the soil water content back to field capacity. Values can be zero, positive or negative.
Fixed application depth (mm water)	The irrigation amount that infiltrates in the field.
Water layer between bunds (mm water)	Threshold for the depth of the surface water layer that should be maintained between the soil bunds (e.g., 5 mm) for the generation of irrigation events for flooded rice.

Table 1. Types of time and depth criteria used for generating irrigation schedules [33].

3. Irrigation charts

Since crop water requirements vary over the growing season, farmers will need to adjust the irrigation during the season. Irrigation calendars are developed to give farmers simple guidelines on how to adjust their irrigation during the growing season. Site-specific calendar-based irrigation scheduling, accounting for local weather conditions and soil characteristics, provides irrigators with an inexpensive yet reliable strategy to estimate irrigation timing and amount [34]. In the design of these calendars, the irrigation water doses are usually considered as fixed. Fixed application depths in combination with variable irrigation intervals lead to the efficient use of irrigation water [35]. The selected value for the fixed application depth depends on the soil type, crop type, irrigation method and equipment. For the sake of simplicity and in order to promote adoption by farmers, the number of irrigation scheduling calendars is kept to a minimum, which means there has to be some generalization. The calendars for each crop are normally based on two planting dates, the major soils and perhaps two different initial soil water content values at the beginning of the irrigation season [36].

The procedure consists of two steps. To obtain reliable guidelines, the simulations need to be run for a long series of historical data. The historical data consist of daily air temperature, and daily, 10-day or monthly reference evapotranspiration. In general, no big variations are to be expected over the years, so one can directly work with mean values. Local soil physical characteristics and crop characteristics of the local variety need to be considered in the simulations. When done, the generated schedules with varying irrigation intervals during the different growth stages are simplified and translated into an easy readable chart.

3.1. Site-specific calendars

AquaCrop was assessed in several cabbage fields in Burkina Faso [32]. Few field data were required. Weather and soil data were provided by the responsible state agencies. Irrigation calendars were registered. Gravimetric soil water content was measured weekly at intervals of 0.2 m up to a depth of 0.6 m. These measurements were repeated three times per treatment, enabling the soil water balance simulation to be evaluated. All needed supplementary drop data were derived for each field by taking weekly dozens of overhead photos (2 m above the canopy) [37].

Figure 2 provides an example of simulated and observed soil water contents in a cabbage plot in Burkina Faso. Field monitoring started 3 weeks after planting. Soil water content exceeded field capacity during most of the growing season. When the soil water content is superior to field capacity, the excess water cannot be bound to the soil particles and drains, leading to water losses by percolation. AquaCrop was prepared to optimize irrigation schedules using local weather, soil and crop data (**Figure 3**). After a first irrigation for field preparation, initial soil water content was assumed to be at field capacity. In the area basin irrigation using a standard motor pump (±30 m^3/h) is the most common practice, and in general, gross application depths of 35 mm are applied. Deep percolation almost certainly occurs as it is nearly impossible to achieve uniform water distribution within a field and the correct rate of water application at the crop level. Since mostly surface irrigation, a field application efficiency of 0.6 was assumed [38]. The resulting soil water is given in **Figure 4**. Soil water content remained well below field capacity and above the readily available amount of water (*RAW*) threshold. *RAW* is the water that a plant can easily extract from the soil. When *RAW* is depleted from the root zone, the soil water content reaches a threshold at which the roots are no longer able to absorb sufficient water to the transpiration demand, and the plant is water-stressed. When soil water content reaches the permanent wilting point, no water remains available for the crops, and the crops will not be able to recover. By keeping the soil water content between field capacity and the *RAW* threshold, water losses due to deep percolation are limited, and crop water stress and yield loss are avoided. A reduction of ±20% in water use is registered, from 555 to 455 mm, while obtaining the same yield, ±52 ton/ha. 20% less water is hence being extracted from the river and becomes available for other crops and farmers, constituting a considerable benefit for the region as a whole.

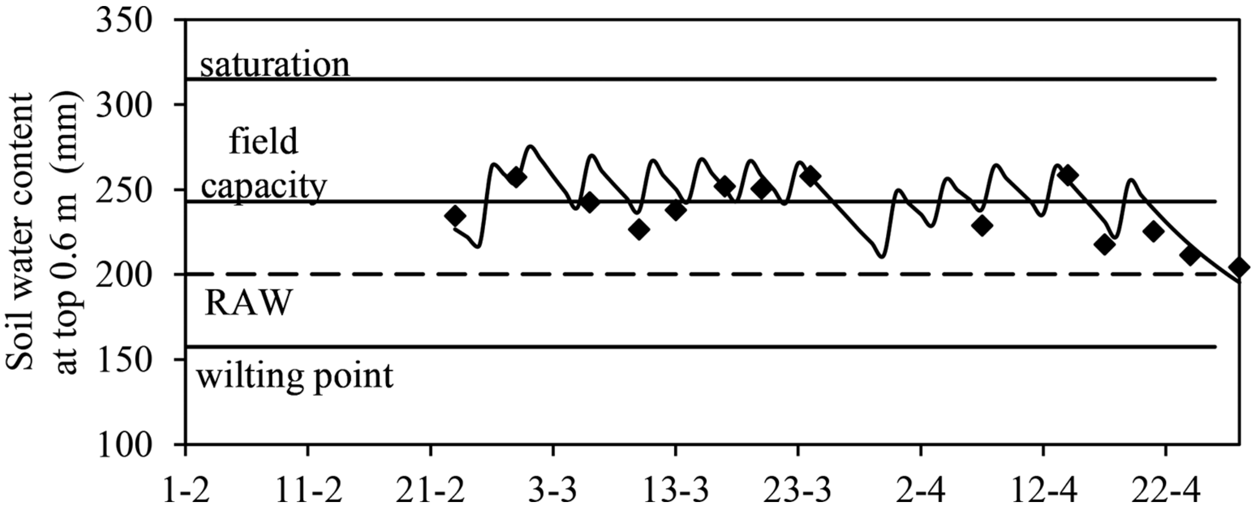

Figure 2. Observed (dots) vs. simulated (line) soil water content for a cabbage plot in Burkina Faso. Each dot is the average of three data. Irrigation: 555 mm; drainage:75 mm; yield: 52 ton/ha.

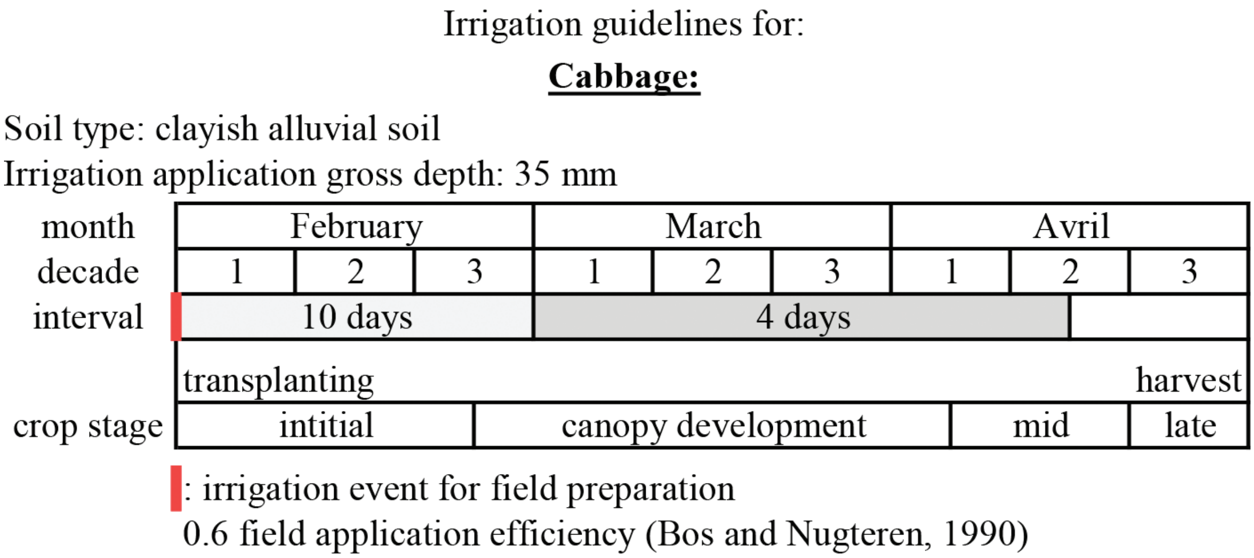

Figure 3. Example of an irrigation chart for cabbage. Cultivated in Burkina Faso on a clayish alluvial soil.

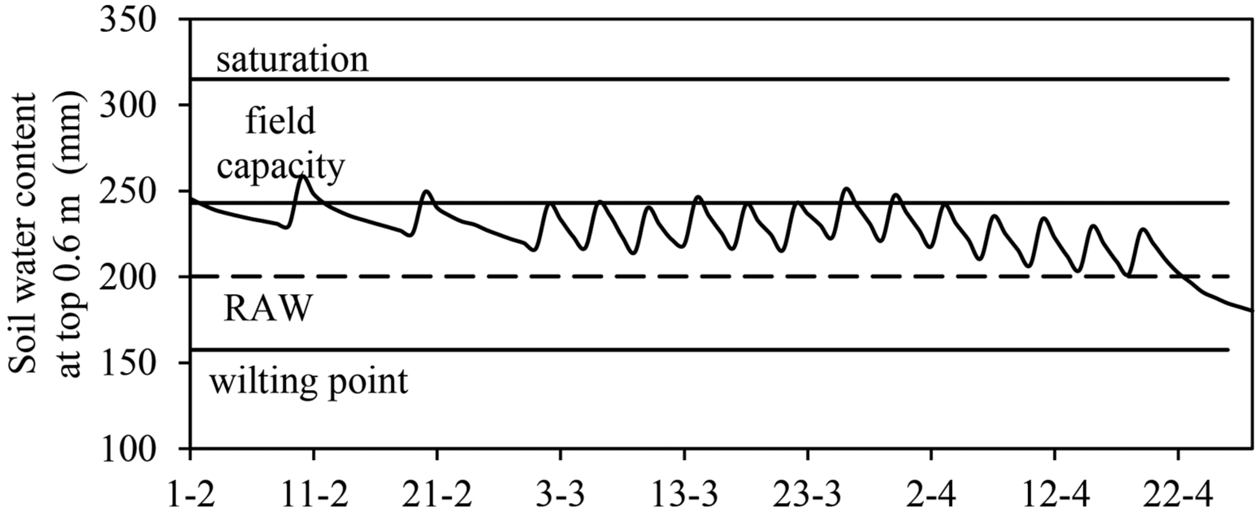

Figure 4. Soil water content when the proposed irrigation schedule is followed. Irrigation: 455 mm; drainage: 1 mm; yield: 53 ton/ha.

With the help of extension workers, the irrigation chart presented in **Figure 3** can be used by farmers [4]. Field application efficiencies, based on the findings of Bos and Nugteren [38], are already included in the gross irrigation application depths. On the back side, indicative durations in hours are given for different motor pump characteristics and field area. Different charts are being elaborated for the region's major crops, soils and irrigation systems.

3.2. Variations and accuracy

For a chart developed for a particular region, it is possible to assign standard weather conditions by analyzing the probability levels of rainfall in that area during different seasons. This could lead to icons to, for example, dry, wet or normal season next to an adapted irrigation calendar [1]. Raes et al. [35, 39] present slightly more elaborated charts for supplementary irrigation, when irrigation is combined with varying levels of rainfall. A variation for deficit irrigation is presented by Geerts et al. [19]. Water applications are limited to drought-sensitive growth stages, in order to maximize water productivity and stabilize, rather than maximize, yields.

To develop a simple tool factors needed to be simplified. In that process, some accuracy is lost. However, Boesveld et al. [1] found that simplified irrigation calendars exceeded detailed irrigation requirement based on modeling by only 2.7% and yielded water savings of 14%. In Fessehazion et al. [34], simple irrigation calendars gave similar irrigation applications, water losses and yields compared to real-time scheduling.

3.3. Real-time scheduling

Previous work has focused on scheduling irrigation over long time frames such as seasonal water allocations. Real-time irrigation scheduling, for example, hourly or daily, has received little attention [40]. Olivier and Singels [41] found that rainfall data and other observations by farmers were often unreliable and propose to go toward a centralized data processing and model execution. A centralized approach also counters the problems of preliminary training and collection of specific data which are not often available for most potential users [6, 42]. Actual research is developing

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smartphone applications to deliver these kinds of optimal irrigation calendars in near real time, based on daily weather data and information inputted by farmers through the application.

FAO also provides the AquaCrop plug-in program, performing identical calculation procedures as the AquaCrop standard program [26]. This version comes as a stand-alone executable without the user interface of the "classic" AquaCrop. By running the program, a list of projects, which contain all the required information for a simulation run, is carried out, and results are stored in output files. The plug-in program facilitates the inclusion of AquaCrop in external applications where iterative or large numbers of runs are required (e.g., [43]).

Figaro (*Flexible and precise irrigation platform to improve farm scale water production*, [44]), BELCAM (*Belgian collaborative agriculture monitoring*, [45]) and iPot (*industrial Potato monitoring*, [46]) are some recent examples of how AquaCrop plug-in is being integrated in information and communications technology (ICT) for agricultural advise, mainly focusing on irrigation and yield prediction. The platforms contain a database with crop, soil and real-time climate data. Farmers are invited to add the location of their fields and basic management characteristics (crop type, date of planting, etc.). A freely available and adapted Java script [47] picks up the required data, launches the AquaCrop plug-in executable and reads out the simulation results: up to date irrigation advice and yield forecast.

Figure 5 sketches the workflow of this approach for a case study in Belgium. A centralized database contains the soil map of Belgium, near real-time meteorological observations covering the whole of the country, a crop database with calibrated crop files for the major crops (potato, maize and winter wheat) and, if entered by farmers, information on field management practices (date of sowing, plant density, etc.), and otherwise default management values are used. On the server, the necessary input files are atomically generated, the AquaCrop plug-in executable launched and its output added to the central database. The main outputs for the moment are yield prevision and irrigation calendars. Through a web application, the data are available at parcel level and summarized for regional level, for the individual farmer but also for all concerned in the domains of agriculture (regional yield estimates and previsions) and environment (regional water balance). For the success of an advisory service, it is necessary to offer the information and tools, which are useful to the farmers and the society, as a whole (environmental benefit, food security, etc.) [7].

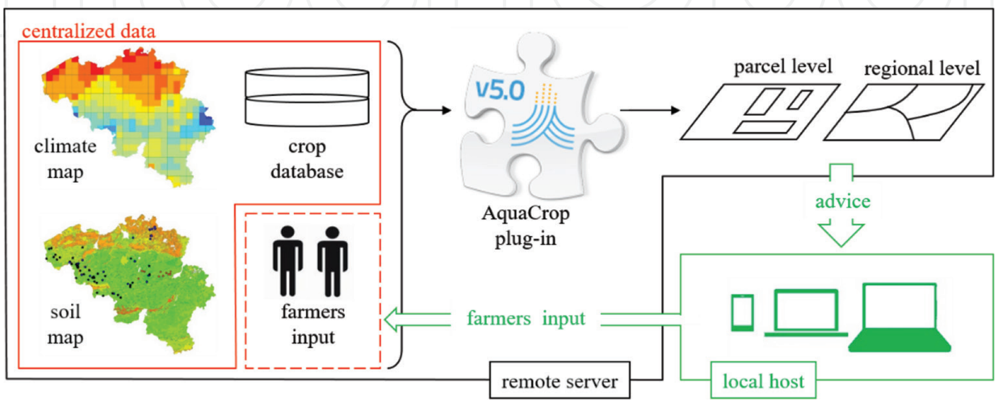

Figure 5. Real-time irrigation advice workflow (β-version under development for Belgian farmers).

4. Discussion and Conclusion

By 2030, irrigated land is predicted to increase by 28% [48], and the pressure on the available water resources will be considerable, even disastrous for some regions. Since a couple of decades, a myriad of irrigation decision-support tools has seen the light to help farmers obtain higher water-use efficiencies. However, a large gap still persists between available efficient water-use technologies and their adoption. Principal reason is the relatively little attention being paid to assist farmers in the adoption of new technologies. The models were often too complicated, high on input demands and/or too specific for only some crops. And local irrigation traditions were not taken into account, and the financial benefits were not clear [7].

FAO developed a simple and robust water-driven field crop model, AquaCrop and its standalone AquaCrop plug-in. The model, which comes already with a large crop database, requires a relatively small number of explicit and often intuitive data and does not require additional fitting. Once calibrated and validated, adapted irrigation schedules can easily be created. Based on AquaCrop simulations, irrigation calendar charts have been developed for use in Belgium, Tunisia, Mozambique and Burkina Faso. For the case of Burkina Faso, water savings amounted to ± 20% when using the proposed irrigation charts, while maintaining the same yield. When no real-time climate data are available, site-specific calendars may be more applicable. These simple and indicative irrigation charts are being transferred by extension workers in order to promote irrigation water savings and thus increase water availability for other users or crops. No data are available on the adoption rate of these irrigation charts. However, a survey was conducted to assess farmers' satisfaction with the overall irrigation advisory service. The general response was very positive, exceeding 90%. Twenty-one percent said they had seen an improvement in their livelihood because of better water distribution, thanks to water savings [49].

The same procedure has also been automated in a client/server application for agricultural advice (yield estimate and irrigation) in Belgium. Data management is centralized, and farmers can have access to personalized irrigation advice when logging into the website. Farmers are invited to add supplemental management information in order to improve the simulation results and the resulting advice; otherwise default, but locally correct, values are used. The tool is being developed in close collaboration with agricultural cooperation and technical centers so that farmers' expectations are taken into account. The application is still in its testing phase, so no information on farmers' appraisal and adoption is yet available. Once fully operational, the adoption rate could be easily evaluated by the numbers of farmers logged into the general server.

External factors and direct and indirect benefits will drive more and more farmers to subscribe to advisory services. Nowadays, the pressure exerted on the agricultural sector by public administration and clients to shift production forms a focus on quantity to a focus on sustainability, and quality is increasing worldwide [2]. The recent implementation of water pricing water policies, as already being required under the European Water Framework Directive, will motivate farmers to invest in technologies (such as decision-support irrigation tools) for improving water management [5]. In general, where resources are scarce and application costs are high, adherence to irrigation advice is also high [7]. Moreover, Qiao et al. [50] documented that farmers participating in an irrigation management program gained additional know-how that improved the water-use efficiency. Also, it is possible that those farmers involved in irrigation scheduling services more easily adopt other management recommendations leading to yield improvements [24].

Author details

Joost Wellens[1]*, Dirk Raes[2] and Bernard Tychon[1]

*Address all correspondence to: joost.wellens@ulg.ac.be

1 Water, Environment & Development Unit, Environmental Sciences and Management Department, University of Liege, Liege, Belgium

2 Division of Soil & Water Management, Department of Earth & Environmental Sciences, K.U. Leuven University, Leuven, Belgium

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