Computers and Electronics in Agriculture 130 (2016) 118–127

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

# Efficient model-based sub-optimal irrigation scheduling using imperfect weather forecasts

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ARTICLE INFO

*Article history:*
Received 27 October 2015
Received in revised form 24 September 2016
Accepted 21 October 2016

*Keywords:*
AquaCrop
Cotton
FIGARO
Irrigation scheduling
Model-based optimization

ABSTRACT

This work describes an efficient model-based procedure for computing seasonal sub-optimal irrigation schedules. The optimization problem is formulated as a multi-objective one, with the objective function consisting of the end-of-season yield and total irrigation. In order to compute the sub-optimal irrigation schedules, a hybrid formulation is presented, according to which a single irrigation event is optimized for the five subsequent days, while irrigation during the rest of the season is assumed to be triggered at some soil water levels which are determined as part of the optimization. This hybrid formulation minimizes the number of decision variables so that solving the optimization problem requires less than one minute on an i5-3470 PC. Such an efficient procedure can be executed whenever new weather forecasts become available and could be integrated in a web-based decision support system. In order to test the proposed approach we used nine years of climatic data from Northern Greece and a locally-calibrated AquaCrop model for cotton crop. We considered three extreme cases with respect to the weather forecasts: perfect weather forecasts available for the whole season; perfect short-term weather forecasts available daily for the five subsequent days and historical weather data available as forecasts for the rest of the season; and only historical weather available as forecasts. The results show that re-computing the sub-optimal solution minimizes the negative effect of imperfect weather forecasts. In the present case-study, even in the worst-case scenario, the multi-year average deviation from optimum was less than 35 mm and 75 kg/ha for irrigation and yield, respectively.



## 1. Introduction

The misuse of the available fresh water resources across Europe threatens sustainable agricultural development and overall economic growth. These considerations have led the European Union to fund the Project FIGARO (Flexible and precIse irriGation plAtform to improve faRm scale water prOductivity) as part of its FP7 Programme. The overall Project's goal is to improve the use of irrigation water via the development and implementation of irrigation strategies that take into account, in real-time, soil water availability, local weather forecasts, crop physiological status and water needs. It is well established that timely irrigation can substantially increase irrigation efficiency and water productivity (Molden, 2003; Fereres and Soriano, 2007; Ahmadi et al., 2010). The development of decision support systems (DSS) which could help farmers use irrigation water more efficiently has been the focus of numerous studies. Although several definitions of DSSs exist, a DSS is generally viewed as an interactive software-based system which helps decision makers compile useful information from various data sources and personal knowledge in order to identify potential problems and make better decisions. With respect to irrigation, a DSS is expected to help growers irrigate their crop (more) efficiently, i.e. achieve high yield while avoiding over-irrigation and water waste, and various approaches have been suggested (Lee et al., 1991; Epperson et al., 1993; Plauborg et al., 1996; Mohan and Arumugam, 1997; Bergez et al., 2001; Shani et al., 2004; Rinaldi and He, 2014). In particular, if weather forecasts and a mathematical model which describes the crop development and production are available, constrained non-linear optimization can be used to compute the irrigation schedule which is optimal in some sense (Linker and Ioslovich, in press; Linker et al., 2015). However, one of the main drawbacks of this model-based approach is its sensitivity to imperfections of the crop-growth model and to inaccuracies of the weather forecasts. Accordingly, both the crop-growth model and the meteorological forecasts should be

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http://dx.doi.org/10.1016/j.compag.2016.10.004
0168-1699/

updated throughout the season using on-site measurements, and the optimization should be repeated based on the updated model and forecasts. The first task, so-called data assimilation, has been considered in a number of studies (Olioso et al., 2005; Thorp et al., 2010; Fang et al., 2011; Ines et al., 2013; Chen et al., 2013; Dong et al., 2013), but is still a complex issue which requires great care. This issue was not considered in the present work, which rather focused on the development of an efficient optimization procedure that could be executed repeatedly in real-time during the season.

A key component of model-based optimization is the crop-growth model, which must describe the crop development, crop evapotranspiration and accumulation of harvestable material sufficiently well, but must not be too complex or involve lengthy computations. The AquaCrop model (Raes et al., 2009a,b; Steduto et al., 2009) distributed by FAO offers such a good compromise between accuracy and simplicity.

One of the crops for which AquaCrop has been validated is cotton (Farahani et al., 2009; Garcia-Vila et al., 2009; Hussein et al., 2011; Heidariniya et al., 2012), and we selected this crop as a case study to test to performance of the proposed approach. More specifically, the proposed approach is illustrated using nine years of historical weather data recorded in Northern Greece, together with a version of AquaCrop which has been calibrated using experiments performed at that location (Tsakmakis et al., 2014). Cotton (*Gossypium hirsutum L.*) is a product of great importance for Greece and much effort has been devoted to improving all of its production steps, from cultivation through production of cotton yarns and fabrics. Greece contributes approximately 80% of the total EU cotton production and cotton accounts for almost 9% of the country's agricultural output. The cotton-cultivated area totals 350,000 ha, representing approximately 13% of the total cultivated land in Greece. However, as water over-use has no direct impact on cultivation and water tariffs are low, Greek farmers tend to 'be on the safe side' and over-irrigate (Karantounias and Dercas, 1998). It is estimated that approximately 55% of the irrigation water is used by the crop, 12% is lost through its transfer, 8% is lost through its application and 25% is lost through evapotranspiration and surface runoff (Danalatos et al., 1998). These figures underline the great potential for water savings.

Several DSSs have been implemented to modernize irrigation scheduling in cotton fields, such as the SADREG DSS in combination with the ISAREG model applied for water saving in Syria (Darouich et al., 2007); the hydroLOGIC DSS utilized in combination with the OZCOT cotton growth model, allowing users to assess different water management options at any crop stage (Richards et al., 2008); the CIDSS developed mostly for drip irrigation fields in China (Chen et al., 2012); and a smart-phone DSS that has been recently developed to provide irrigation management advice combining remote sensing data, weather predictions and on-line field data (Vleeshouwer et al., 2015). By comparison, the present work focused on the optimization methodology and the influence of weather forecasts inaccuracy on the results. While the impact of imperfect weather forecasts on irrigation scheduling has been previously investigated in several studies (Venalainen et al., 2005; Gowing and Ejieji, 2001; Lorite et al., 2015; Wang and Cai, 2009), in most cases the irrigation schedule was not derived using a strict optimization framework. A notable exception is the work of Wang and Cai (2009) who used a genetic algorithm to determine the optimal timing and water amount of irrigation events assuming perfect weather forecasts for either the entire season or only two weeks. In the latter case the optimization was performed sequentially on non-overlapping two-week time windows. By comparison, in the present work the optimization criterion consists of the end-of-season yield and seasonal irrigation.

## 2. Materials and methods

### 2.1. AquaCrop

AquaCrop is a water-driven model in which crop development is determined by transpiration. Previous studies have shown that this model can predict with reasonable accuracy the total biomass and yield of a wide range of crops in response to various irrigation strategies (Garcia-Vila et al., 2009; Heng et al., 2009; Araya et al., 2010; Andarzian et al., 2011; Stricevic et al., 2011; Abedinpour et al., 2012; Battilani et al., 2015). AquaCrop has also been used in studies investigating the impact of climate change on food production (Deb et al., 2015). The development of the canopy cover is used for the simulation of total biomass, and yield is calculated as the product of biomass and the harvest index (HI). The relationship between HI and stresses is crop-dependent and varies with crop developmental stage. Water stress affects crop development via four stress coefficients (which affect leaf expansion, stomata closure, canopy senescence and HI).

With respect to the proposed approach, one of the key features of AquaCrop is that it can generate an irrigation schedule that ensures that the soil water content remains above some (time-varying) threshold specified by the user. In this mode of operation the user splits the season into a number of contiguous periods and specifies two parameters for each period: the soil moisture at which irrigation is triggered (allowable depletion in mm or % readily available water) and the amount of water to be supplied (absolute amount in mm or replenishment to field capacity - X mm). The output of the corresponding AquaCrop simulation includes, in addition to all the variables related to crop development and soil water content, the dates and amounts of the irrigation required to maintain the soil water content above the prescribed level.

### 2.2. Optimization

In its simplest form, the optimization problem can be formulated as

$$\text{Find}(n, d_1, w_1, d_2, w_2, \cdots, d_n, w_n) \quad \text{such that} \quad Y \rightarrow \max \tag{1}$$

where $Y$ denotes the yield, $n$ denotes the number of irrigation events, and $d_i$ and $w_i$ denote the date and amount of the ith irrigation event, respectively. Various types of constraints (such as monthly or seasonal water quotas imposed by national legislation, or minimum period between irrigation events) can be readily added to this formulation. Ioslovich et al. (2014), Linker and Ioslovich (2016) and Linker et al. (2015) recently showed how non-linear constrained optimization can be used to solve this problem. Furthermore, they showed how by repeating the computations with different values of the seasonal water quota, this approach can be used to obtain the water production function (WPF), which, for a given environment, expresses the maximal yield achievable as a function of seasonal irrigation. However, solving the problem formulated in (1) is time consuming computer-wise and is not suitable for real-time applications, especially if one desires to revise the solution when updated weather forecasts become available. In the present work, we present a methodology suitable for such real-time applications, which is based on two main features.

1. Rather than solving repeatedly a maximization problem with various quota constraints, as suggested in Ioslovich et al. (2014), Linker and Ioslovich (2016) and Linker et al. (2015), we formulate a multi-objective minimization problem, as:

$$\text{Find the irrigation schedule such that} \left(-Y, \sum_{k=1}^{n} w_n\right) \rightarrow \min \tag{2}$$