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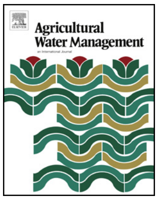

Assessment of optimal irrigation water allocation for pressurized irrigation system using water balance approach, learning machines, and remotely sensed data

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ABSTRACT

Efficient irrigation can help avoid crop water stress, undesirable levels of nutrient leaching, and yield reduction due to water shortage, runoff or over irrigation. Gains in water use efficiency can be achieved when water application is precisely matched to the spatially distributed crop water demand. Thus, greater irrigation efficiency will facilitate quality crops and help to minimize additional agricultural and financial inputs. Irrigation efficiency is defined based on indicators such as irrigation uniformity, crop production, economic return, and water resources sustainability. This paper introduces a modeling approach for optimal water allocation relative to maximizing irrigation uniformity and minimizing yield reduction. Landsat images, local weather data, and field measurements were used to develop a model that describes field conditions using a soil water balance approach. The model includes two main modules: optimization of water allocation and forecasting the components of soil water balance model. Each module includes two sub-modules that consider two objectives. The optimization sub-module use genetic algorithms (GA) to identify optimal crop water application rates based on the crop type, growing stage, and sensitivity to water stress. Results from the optimization module are passed to the forecasting sub-module, which allocate water through time across the area covered by the center pivot based on the results from the previous period of irrigation (previous day) and the operational capacity of the center pivot irrigation system. The model was tested for a farm installed with alfalfa and oats and equipped with a center pivot in Scipio, Utah. The model products were assessed based on ground data (soil moisture measurements) under optimized and simulated (irrigator decisions) center pivot operations. Based on the simulation and optimization results obtained from the model, study area irrigator could use up to 20 percent less water (saved quantity over total quantity of water) over the growing season, compared to traditional operating procedures, without reducing the benefits.

1. Introduction

Irrigation plays an essential role in the agricultural productivity of a farm, especially in arid areas. Gains in water use efficiency can be achieved when water application is precisely matched to the spatially and temporally distributed crop water demand. In the past few decades, new technologies have played an important role in improving irrigation water allocation. For example, precision agriculture technologies have significantly advanced irrigation scheduling. Electronic devices for continuous monitoring of soil moisture and climatic conditions are widely used for more precise irrigation management of hay as a source of food for animals (Sammis, 1981; Irmak et al., 2008; Cruz-Blanco et al., 2014). Satellite sensors, such as MODIS, Landsat, and GOES, and remote sensing technology can be used to estimate crop water use and offer the potential for better water management in irrigated areas as a continuous, automated, and easy-to-use source of information (Fares et al., 2006; Cammalleri and Ciraolo, 2013; Hassan-Esfahani et al., 2014 and 2015). Optical and thermal remote sensing data from ground-based and space-borne platforms have been used to quantify water stress and evapotranspiration at field and district scales (Taghvaeian et al., 2013). Infrared thermometry has been used in conjunction with a few weather parameters to develop non-water-stressed and non-transpiring baselines for irrigated maize in a semi-arid region. Taghvaeian et al. (2012), Torres et al. (2011), Allen et al. (2007), and Bastiaanssen et al. (2005) have used remotely sensed data to calculate daily evapotranspiration.

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In addition to new technologies and satellite information, computer modeling have become popular for irrigation management. Many existing models have been developed to simulate on-farm irrigation water demands based on climate-soil-plant systems (Ahmadi and Merkley, 2009). Some optimizing irrigation planning models attempt to obtain the optimum irrigation quantity values to satisfy the objective function and constraints. These optimization models for irrigation planning have received extensive interest. Kuo et al. (2000) developed a model based on on-farm irrigation scheduling and a simple Genetic Algorithm (GA) optimization method for decision support in irrigation project planning. Delavar et al. (2012) developed a real-time modeling approach for optimal water allocation during a drought. Moghaddasi et al. (2009) developed a model for optimal allocation of water among different crops and irrigation units. Ines et al. (2006) presented an innovative approach to explore water management options in irrigated agriculture using combined remote sensing-simulation modeling and genetic algorithm optimization.

Learning machines have also been used to solve problems related to water resources management. Pulido-Calvo and Gutierrez-Estrada (2008) used computational neural networks (CNNs) to model irrigation demand and forecast water demand. Kashif Gill et al. (2007) presented soil moisture data assimilation research that employed learning machines and a soil moisture prediction model using support vector machines.

The present work uses Landsat satellite images, field measurements, and crop-related remote sensing algorithms to demonstrate the adequacy and accuracy of a model for optimizing irrigation water allocation and simulating soil moisture conditions among the 24 irrigation sectors in the study area. The accuracy of the model was checked using a soil water balance approach for the crop growing cycle.

2. Model components review

2.1. Irrigation scheduling

Irrigation managers use a process called irrigation scheduling to determine the frequency and duration of irrigation events, based on the application rate of the irrigation equipment, distribution uniformity (Delavar et al., 2012), soil infiltration rate, available water capacity (Moghaddasi et al., 2009), soil water holding capacity, and crop characteristics.

2.2. Irrigation scheduling based on models

Optimization is the process of choosing the best solution (considering some criteria) from a set of available alternatives. In a common case, an optimization problem includes maximizing or minimizing a real function by systematically selecting input values from within an available set and computing the value of the objective function (Bradley et al., 1977). In the current study, the spatially distributed values for irrigation rates are optimized based on specific criteria.

2.2.1. Genetic algorithms

Genetic algorithm have been applied in many studies as search heuristics to find optimal solutions to non-linear problems, and they constitute a routinely used and useful method that mimic the process of natural selection. The priorities of GA over other potential algorithms are stated best by Goldberg (1989). GAs differ from conventional optimization and search procedures in the following ways: (1) GAs work with a coding of the parameter set, not the parameters themselves; (2) GAs search from a population of points, not a single point; (3) GAs use objective function information, not derivatives or other auxiliary knowledge; and (4) GAs use probabilistic transition rules, not deterministic rules.

2.2.2. Optimization objectives

In the current study, the spatially distributed values for irrigation rates are optimized considering two different objectives targeted toward saving water. These objectives were selected based on criteria regarding crop type, soil texture type, availability of water, irrigation system capacity and restrictions, growing stage, or sensitivity to water stress. Both are fundamental approaches to optimize irrigation water allocation and are summarized as follows:

- Maximizing soil moisture uniformity.
- Minimizing yield reduction.

2.2.2.1. Gini coefficient. The Gini coefficient is a measure of statistical dispersion. It ranges from 0 to 1 and measures the inequality among values of a frequency distribution. It was first introduced for measuring the inequality of income distribution of a nation's residents and was later applied in other fields of studies (Cullis and van Koppen, 2007). A Gini coefficient of zero describes perfect equality, where all values are the same (everyone has the same income), and a Gini coefficient of one (or 100%) expresses maximal inequality among values (where only one person has all the income). Eq. (1) represents this concept as the objective function (Gini, 1912).

$$\mathrm{GINI} = \frac{2\sum_{n}^{i=1} i \times y_i}{n\sum_{n}^{i=1} y_i} - \frac{n+1}{n} \tag{1}$$

where n is the number of measurements and y is the measured values. The GA minimizes the Gini coefficient to seek a uniform water application distribution by changing irrigation rates in space and time, subject to system operational constraints.

2.2.2.2. Yield function. The second objective function was based on a yield function. FAO No. 66 (Steduto et al., 2012) presented a linear relationship between crop yield and water use by an equation where relative yield reduction is related to the corresponding relative reduction in evapotranspiration (ET). Eq. (2) represents this relationship as the objective function (FAO. Paper No. 66). This function has been used in other studies (Delavar et al., 2012; Moghaddasi et al., 2009):

$$\left(1 - \frac{Y_a}{Y_x}\right) = K_y\left(1 - \frac{\mathrm{ET}_a}{\mathrm{ET}_x}\right) \tag{2}$$

where K_c is the crop coefficient and Y_a, Y_x ET_a and ET_x are actual and maximum yield and actual and maximum evapotranspiration, respectively. As with the spatial uniformity objective, the GA minimizes yield reduction by changing irrigation rates in space and time, subject to system operational constraints.

3. Materials and methods

3.1. Study area

The study area is a farm of approximately 84 acres in Scipio, Utah, equipped with a modern center pivot sprinkler irrigation system with the capacity of 610 GPM. The crops for this farm, grown from April to October, are alfalfa in three-quarters of the field and oats in the north-east quarter (Fig. 1). Generally, the center pivot lateral rotates clockwise at a constant speed and supplies irrigation water from an upstream reservoir. The center pivot is computer programmable, and the smallest portion of the farm that can be individually irrigated is a 15 degree arc, which is considered as an irrigation sector in this study. These 15 degree arcs were numbered